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GEOLOGICAL MAGAZINE

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Aspects of the Geology of the Scotia Arc

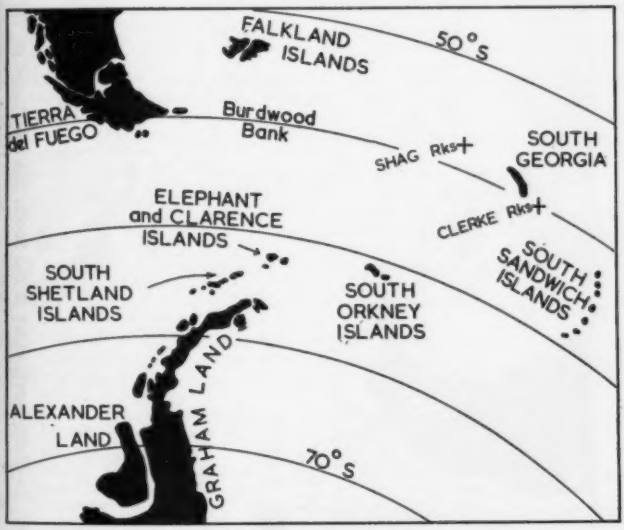
By D. H. MATTHEWS

ABSTRACT

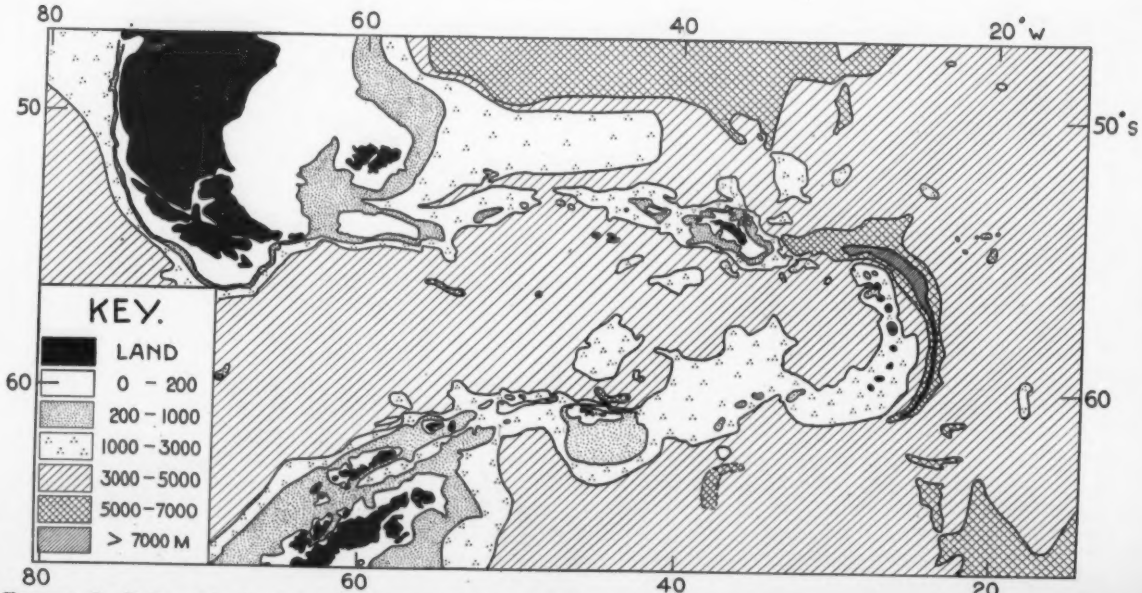
A review is given of the geology of the islands of the Scotia Arc. The provenance of the sedimentary materials is considered and it is concluded that the islands probably represent areas with a crustal structure of a continental type. The crustal structure of the Scotia Sea area is briefly compared with that of the Caribbean.

I. INTRODUCTION

NEAR the tip of South America, in Tierra del Fuego, the Andes curve round to the east before they are lost in the sea. Farther south, on the opposite side of Drake Passage, the narrow mountainous



TEXT-FIG. 1.—Map of the Scotia Sea area showing the names of the principal localities referred to in the text. Based on map D.C.S. 960, published by the Directorate of Overseas Surveys in 1955.



TEXT-FIG. 2.—Bathymetric chart of the Scotia Sea area based on the chart published by the Bureau International Hydrographique (1952). Soundings in metres

peninsula of Graham Land projects from the Antarctic continent towards South America and it also curves round to the eastward near its tip. Between Graham Land and Tierra del Fuego an elongated loop of islands and shallow banks extends the line of the mountains for 1,500 miles eastwards into the deep South Atlantic. This island arc was originally called the *Southern Antilles*, emphasizing its similarity to the Caribbean island arc, but the name *Scotia Arc* is to be preferred. The principal islands of the arc are named in Text-fig. 1. The deep sea enclosed by the Scotia Arc and by Drake Passage is called the Scotia Sea. The purpose of this paper is to draw attention to some broad aspects of the geology of the Scotia Arc which appear to be relevant to a consideration of the crustal structure of the whole Scotia Sea area.

The idea that the islands of the Scotia Arc are in some way geologically continuous is by no means new. An early account of the geology of the region was given by Suess (1909, p. 489), who was able to quote a passage written by Arctowski in 1895 suggesting " that the Andes are to be seen again in Graham Land ". Suess indicated that the

---

NOTES ON TABLE 1

* Recent volcanic activity.
(a) Early flows pyroxene-andesites, late flows olivine-basalts
(b) Piso de Navidad.
(c) Basal conglomerate contains pieces of the Andean batholith.
(d) Andesitic volcanics and marine intercalations. Tithonian-Neocomian.
(e) Unconformity dies out in Tierra del Fuego.
(f) 1. acid volcanics (keratophyres), 2. argillites and tuffs, 3. greywackes and mudstones.
(g) Carbonaceous mica-schists, metamorphic quartzites, and greenstones.
(h) Carbonaceous schists overlie *para*-schists of almandine grade.
(i) Outcrop not located. Known only as gigantic erratic blocks on the beach (Tyrrell, 1945, p. 65). Contains water-worn boulders of andesite and altered tonalite.
(j) A tiny patch rests on James Ross Island Volcanics at Cockburn Island.
(k) Vesicular olivine-basalts.
(l) Sandstones and mudstones with tuffs near the top. Contain fossil penguins and invertebrates.
(m) Sandstones, calcareous sediments, and shale, with thin coals. Lr. to middle Campanian fauna. Slight folds about N.–S. axes.
(n) The Upper Jurassic Volcanics (andesites, rhyolites, and tuffs) are widespread in Graham Land.
(o) The sedimentary sequence quoted is for the Hope Bay region. Arkosic Jurassic plant beds occur at Cape Longing. Folds run N.E.–S.W. at Church Point.
(p) Probably Carboniferous. Fold axes at Mt. Bransfield run N.E.–S.W., parallel to Trinity Peninsula.
(q) *Ortho-* and *para*-gneisses of almandine grade in the Marguerite Bay region. Strike N.E.–S.W.
(r) Sandstones and shales with an Aptian fauna (lamellibranchs, annelids, and ammonites) resting on a thick basal conglomerate.
(s) Estuarine (?) sediments with brachiopods, belemnites and plant remains overlie thick aqueous tuffs.

TABLE 1.—STRATIGRAPHICAL

	SOUTH CHILE		Shag Rks.	SOUTH GEORGIA	Clerke Rk.	SOUTH SANDWICH ISLANDS
	ANDEAN GEOSYNCLINE	MAGELLAN GEOSYNCLINE				
RECENT PLEIST.	✳ present	alluvial and glacial deposits			?	✳ andesites to dacites
PLIO.	ranges formed — Vulcanism	terrestrial			dykes	
MIOCENE	marine transgression (b) — Vulcanism	sandstones, tuffs and basalts			basic	
OLIGO.		NW (e) SE				
EOCENE	marine incursions ?	NW terrestrial — SE marine				
UP^{r} CRET.	Senonian seds. cgl. (c) Senonian	marine seds. cgl. (c) ANDEAN BATHOLITH (e)		post-Aptian intrusion & folding	granite ?	
L^{r} CRET	Aptian Porphyrite	3. 2. Yahgan Series (f)		Cumberland Bay		
UP^{r} JURASSIC	formation (d) non-sequence	1. Serie porfírica		type		
MID JURASSIC	andesites & marine volcanic breccia			grey-wacke		
L^{r} JURASSIC	seds Keratophyres non-sequence ?			facies		
TRIAS	3. Norian shale 2. Keratophyres + plants 1. conglom.			Sandebugten type		
PAL.	3. slate, lst., sst. & tillite 2. slate & cgl. 1. Devonian slate	shales, sst. & lst. (Up^{r} Palaeozoic)	schists ?			? dredged dolomitic mudstone
? PRE-CAMBRIAN	meta-sedimentary basement	schist (g) gneiss (Staten Isl.)				? schist

TABLE

SOUTH ORKNEY ISLANDS	ELEPHANT and CLARENCE ISLANDS	SOUTH SHETLAND ISLANDS	GRAHAM LAND	
			PENINSULA AND ISLANDS	ALEXANDER LAND
		✳ Deception Is.& Penguin Is. gp.		
			Pecten Conglomerate (j)	
		Pyroxene – andesites and aqueous tuffs with plants	James Ross Is. Volc.[s] (k) Seymour Is. Series (i)	
		[cgl. (i)] Andean Batholith	Andean Granite – Gabbro Intrusive Suite	
Cgl. shale dolerite dykes?			Snow Hill Is. Series • Cape Longing Series (m)	
				marine seds. cgl. (r)
		Upper Jurassic Volcanics (n)	Upper Jurassic Volcanics (n)	estuarine seds. tuffs (s)
Derived Series			plant beds conglomerate (o)	
Greywacke – Shale Series			Trinity Peninsula Series greywackes (p) Early Pal. Volcanics Early Pal. Granites	
Basement schists (h)	carbon-aceous phyllites ~~~? schists		Basement Complex (q)	

connection between South America and Graham Land should be sought in the islands of the Scotia Arc and, after mentioning the oceanographic work of the Scottish National Antarctic Expedition, 1902–4, which had resulted in the discovery of a submarine ridge connecting the islands, he predicted that a deep trench would be found east of the South Sandwich Islands in a position corresponding to that of the Puerto Rico trench which lies to the east of the Caribbean arc. This prediction has been verified by subsequent hydrographic work and particularly by the work done by R.R.S. *Discovery II* (Herdman, 1948). Although the soundings are still sparse and the existence of breaches in the submarine ridge has been argued it is generally accepted as a working hypothesis that the mountains of Graham Land are topographically connected with the Andes by a submarine ridge which carries on it the mountainous islands of the Scotia Arc. This ridge has been named the " Scotia Ridge " (Herdman *et al.*, 1956). Text-fig. 2 is a bathymetric chart of the area. A detailed discussion of the bathymetry has been given by Herdman (1948). Joyce (1951) has drawn attention to the fact that the ridge consists in places of two or even three parallel ridges separated by deeps, but many of Joyce's stratigraphical correlations are now in need of revision.

Further evidence of the continuity of the Scotia Arc comes from the study of seismology, although until the start of the International Geophysical Year this study was handicapped by the sparse distribution of observatories in the southern hemisphere. Gutenberg and Richter (1954, p. 42) conclude that " Epicentres of shallow shocks appear to follow the structural loop, being most frequent near the South Sandwich Islands ". The South Sandwich chain of volcanic islands shows features typical of an active island arc: epicentres of shallow shocks are located under the deep trench on the convex side of the arc and deeper epicentres are located under the islands.

As a result of the evidence outlined above, it may be concluded that the Scotia Sea is enclosed on three sides by a continuous or almost continuous submarine ridge which carries islands upon it and is somewhat tectonically active. It will be shown that some of the islands are far from being typically oceanic and this suggests that the crustal structure beneath the Scotia Sea may not be typical of that normally found beneath the deep oceans.

Systematic accounts of the geology of the Scotia Arc have been given by Wordie (preface to Tyrrell, 1945), Barth and Holmsen (1939, esp. p. 60), and Holtedahl (1929, pp. 104–117) who pointed out (p. 117) that " geologically and geographically the region is a mixture of oceanic and continental characters ". A historical account of geological investigations in the area has been given by Adie (1957a, and 1958).

The part of the Table referring to Graham Land is based upon a Table given by Adie (1953). No direct evidence about the age of the Andean Intrusive Suite is available outside America. Adie (1955, p. 4) considered the age of the post-Jurassic Andean Granite-Gabbro Intrusive Suite in Graham Land by analogy with the comparable intrusions in Patagonia described by Hauthal and concluded that the most probable age is early Tertiary (post-Middle Campanian and pre-Lower Miocene). He considers that the intrusions in South Georgia and the South Shetland Islands should also be shown in the Lower Tertiary in Table 1. But evidence cited by Cristi (Jenks, 1956, p. 204) suggests an Upper Cretaceous age for some of the Andean Batholith in South America, and in Table 1 the writer has preferred to indicate the uncertainty and possible variation in the age of the Andean intrusives of the Scotia Arc, arbitrarily equating those in South Georgia with South America and those in the South Shetland Islands with Graham Land.

If the Scotia Ridge forms a part of the Andean chain, the orogenic history of the islands of the Scotia Arc should resemble that of the rest of the chain. Table 1 presents some account of the stratigraphy of the area and is based on recent sources. The columns headed "Southern Chile" have been taken without modification from the account given by Cristi (Jenks, 1956). The column headed "Andean Geosyncline" refers essentially to the area north of 45° S., while the column "Magellan Geosyncline" refers to Chilean Tierra del Fuego and the area as far north as lat. 45° S. The other columns are taken from the more recent sources referred to by Adie (1958).

In order to examine the hypothesis that the Scotia Ridge represents a part of the Andean chain it would be necessary to compare the details of the orogenic histories of points round the arc from South America to Graham Land. Enough is known of the stratigraphy of the islands to suggest that the record is extremely incomplete and although interesting points emerge even from the uncritical juxtaposition of recent accounts shown in Table 1, it is not intended to pursue this detailed stratigraphical approach further in this paper. Stratigraphical work is proceeding with great vigour both in the Falkland Islands Dependencies and in South America and it is hoped that a stratigraphical review will soon be available. In this paper it is intended to examine the broader aspects of the geology of the islands of the arc and the problem of the provenance of their sedimentary rocks. The arc will be considered clockwise, starting with the Burdwood Bank.

II. Geology of the Islands of the Arc

The Burdwood Bank is an isolated area of shallow water lying about 200 miles east of Staten Island and separated by a trough of deep

water from the Falkland Islands to the north. (See Text-fig. 2.) (The Falkland Islands show geological resemblances to South Africa and do not form part of the Scotia Arc.) Suess (1909, p. 490) mentions that volcanic rocks have been brought up from the Burdwood Bank and Macfadyen (1933) has described dredged fragments of greenish shale and argillaceous limestone with an associated fauna of foraminifera of Upper Cretaceous (Senonian) and Lower Tertiary age. He believes that these rocks are exposed on the bank.

The next land is at Shag Rocks which lie on the ridge about 150 miles west of South Georgia. Nineteen stones dredged from this locality by R.R.S. *Discovery II* have been described by Tyrrell (1945) from whom this account is taken. Of these stones, three were quartz-chlorite-calcite vein rocks and fifteen were " greenstones " (low grade schists with tremolite, clinozoisite, epidote, chlorite, quartz, and albite, probably derived from basalts). One was a quartzitic arkose. The homogeneity of this collection suggests that the rocks dredged were not erratics, but that low grade schists, similar to the Cape Valentine group of Clarence Island, are exposed near Shag Rocks.

Much has been written about South Georgia. Accounts have been given by Holtedahl (1929) and Tyrrell (1930), but the present account is largely based on Trendall (1953 and 1959). Two stratigraphical units have been recognized:—

(2) Cumberland Bay type. Tuffaceous greywackes with interbedded spilites and basalts near the top. Rocks referred to the top of the Cumberland Bay type have yielded an Aptian fauna at one locality.

(1) Sandebugten type. Quartzose greywackes which are lithologically similar to the greywackes of the South Orkneys and the Trinity Peninsula Series (Graham Land) and may be Upper Palaeozoic in age.

The older rocks (the Sandebugten type and parts of the Cumberland Bay type) have been very violently folded about axes parallel to the length of the island. The greywackes of the two groups show certain lithological and structural differences (Trendall, 1959, p. 41): the sedimentary material of the Cumberland Bay type could all have been derived by the weathering of volcanic rocks, but the Sandebugten type contains fragments of sandstone and metamorphic quartzite as well as lava. The status of the boundary between these two groups has been debated, but Holtedahl and Trendall incline to the view that both groups belong to a single series of great thickness (> 10 km.) and of Mesozoic age, although they have not dismissed the possibility that the Sandebugten type was deposited during the uppermost Palaeozoic.

The rocks at the eastern end of the island are cut by a granite-gabbro intrusive complex. Trendall has described foliation in the marginal acid rocks of the intrusion and in a huge xenolithic block of quartz-granulite, and has concluded (p. 43) that the whole intrusive complex was paratectonic and therefore post-Aptian in age. Adie (personal communication) considers that the intrusive complex is Andean in age and that some, if not all, of the xenolithic foliated rocks are enormous rafts derived from an underlying metamorphic basement.

There are many unsolved problems on South Georgia, but it is clear that a great thickness of sedimentary rocks is present. The sediments are largely of volcanic origin, but they include some arenaceous material, especially in their lower parts, and rare calcareous beds and fossil wood have been recorded, strongly suggesting the influence of a nearby landmass of considerable size. The presence of acid intrusive rocks further emphasizes that South Georgia, although far out in the South Atlantic, is a most atypical oceanic island.

Seventy miles east of South Georgia lies Clerke Rock. Holtedahl (1929, p. 102) has described specimens collected from this locality which indicate that the rock is granite cut by basic dykes. This intrusion is provisionally regarded as Andean in Table 1, but its dating by mass spectrographic methods would be of the greatest interest.

Of the ten islands of the South Sandwich group, five are still actively volcanic. The volcanic rocks have been described by Tyrrell (1945), who mentions olivine-basalts (almost andesites), true andesites, and a dacite and suggests that the chemical results indicate affinities with the Lesser Antilles rather than with either the Recent volcanics of the Andes, or the lavas of the Recent volcanoes in the South Shetland Islands. Whilst all the major islands of the South Sandwich Group are believed to be formed of recent volcanic rocks, one inaccessible islet, Freezeland Peak near Bristol Island, has a different appearance. Specimens of schist were taken from a block of floating ice near Bristol Island. Tyrrell (1945, p. 98) states that " as the metamorphic fragments were closely associated with scoria which indubitably came from Bristol Island, it seems probable that they too were derived from that locality ". It would be of the greatest interest to prove or disprove the presence of Basement Complex rocks in the South Sandwich Islands either as outcrops or as xenoliths in the lavas.

Passing westward from the South Sandwich Islands along the most sparsely sounded part of the ridge the next land is the South Orkney Islands. Work up to the war was summarized by Tilley (1935). The results of further work carried out by the Falkland Islands Dependencies Survey are in the press (Matthews *et al.*, 1959). The succession established in the South Orkneys is as follows :—

(4) Conglomerate

(3) (Derived Series)
(2) Greywacke-Shale Series
(1) Basement Complex (metasediments).

The Basement Complex outcrops at the western end of the group. It consists of a substantial thickness of *para*-schists of garnet grade, dominantly quartz-mica-schists with subordinate *para*-amphibolites and marbles. The interbedded marbles, amphibolites, and psammitic schists at the base of the succession, on Signy Island, appear to be the products of metamorphism of an alternating succession of limestone, argillo-calcareous sediments, and sands *of shallow water facies*. At the western extremity of the main outcrop, the more varied schists are overlain, apparently without unconformity, by carbonaceous schists or phyllites without almandine and twenty miles further west the Inaccessible Islands are formed of "chlorite epidote schist... representing a basic igneous rock of doleritic character" (Tilley, 1935, p. 389). This uppermost group of the Basement Complex resembles the Cape Valentine series of Elephant Island. Both groups of the Basement Complex show bedding foliation and have been violently folded about axes trending approximately north-south. Traces of subsequent minor folding have been observed.

The thick Greywacke-Shale Series is exposed at the eastern end of the group. Tilley concluded that these rocks were formed from the waste of sodic igneous rocks, felsites, rhyolites, and the older metamorphic series. Fossils found in the greywacke-shale were originally thought to be Ordovician in age (Pirie, 1905), but a re-examination has suggested that the fossils are plant remains and the rocks are provisionally correlated with the older greywackes of South Georgia and with the Trinity Peninsula Series (Carboniferous) of Graham Land (Adie, 1957b, p. 22). The Greywacke-Shale Series has been vigorously folded about axes which trend N.N.W.–S.S.E. and the effects of this folding can also be traced in the Basement Complex.

The central area of the South Orkneys is occupied by a flat-lying, coarse-bedded conglomerate more than 1,700 ft. thick. There are indications that the bulk of the conglomerate was formed on land. Besides abundant detritus from the Basement Complex and the Greywacke-Shale Series, there are rare phenoclasts from another source. This source, whose outcrop has not been located, constitutes the Derived Series. The rocks of the Derived Series are:—

(*a*) Calcareous grits with brachiopods, lamellibranchs, belemnites, and plants of Mesozoic, probably Jurassic, age.
(*b*) Current-bedded sandstones with plants.
(*c*) Felsite, spherulitic felsite and rhyolite (Tilley, 1935, p. 386).

The conglomerate is known to be exposed on two of the three

principal islands of the group. The outcrops vary in bulk composition, locally derived material being the most abundant in each case. The rocks of the two main outcrop areas are not necessarily coeval. The conglomerate on Powell Island contains unidentified plant fragments including fronds. At the one locality on Coronation Island where the base of the conglomerate has been located, a few feet of sheared black shale are interposed between the coarse conglomerate and the underlying schists. The shale contains a poorly preserved fauna of minute lamellibranchs and brachiopods which are probably Cretaceous in age. The conglomerate is provisionally regarded as being of Cretaceous age. Although the conglomerate is essentially flat-lying there are indications of very gentle folding about axes trending east–west. In the Basement Complex on Coronation Island some structures superimposed upon the older folds are also interpreted as being due to north–south compressive forces.

Unsheared dykes of olivine-dolerite cut the schists on Coronation Island and, with the exception of the pebbles in the conglomerate, are the only igneous rocks known in the South Orkneys.

It is concluded that the rocks of the South Orkneys are entirely of a continental or shallow water aspect. There is nothing " oceanic " about the South Orkney Islands.

West of the South Orkneys, the Scotia Ridge is divided into two by a trough of relatively deep water extending from the 5,000 m. " deep " situated immediately north of the South Orkneys as far as the Bransfield Strait which separates the South Shetland Islands from Graham Land (Herdman, 1948). The Elephant and Clarence Island group lies on the opposite side of this feature to the South Orkney Islands, but what is known of the geology reveals a strong resemblance between the metamorphic rocks of the two areas.

Two groups of schists have been recognized on Elephant Island (Tilley, 1930; Tyrrell, 1945).

(2) Rocks of the northern part of the island (Cape Valentine):—

Phyllites with fine texture and glossy cleavage surfaces. The rocks belong to the chlorite zone and the dominant type is a carbonaceous quartz-albite-chlorite-sericite-schist. They occupy the northern part of Elephant Island and their folding runs roughly parallel with the Scotia arc. Their resemblance to the uppermost part of the Basement Complex in the South Orkney Islands has already been mentioned.

(1) Rocks from the southern part of the island (Lookout Harbour):—

These are mica-schists, *para*-amphibolites and marbles of almandine grade. They occupy the southern part of Elephant Island and

their strike is unknown. Specimens from Cape Bowles in the collections of the Department of Mineralogy and Petrology at Cambridge are indistinguishable from specimens of the lower part of the Basement Complex in the South Orkneys.

Professor Tilley has concluded that the high grade schists of the Lookout Harbour group were originally sediments containing detrital albite and " ranging from limestones to impure types giving the amphibolites and garnet-hornblende-schists rich in albite " (1930, p. 62). He also regards the low grade schists of the Cape Valentine group as being metamorphosed normal sedimentary rocks. Tyrrell (1948, p. 77) concludes that some of the original sediments may have been andesitic dusts. Tyrrell (p. 88) regards all the metamorphic rocks as the products of the low grade metamorphism of a greenstone-greywacke-mudstone assemblage formed *in situ* by the submarine weathering of spilites, and similar to the Yahgan formation of Tierra del Fuego.

Thirty miles south of Elephant Island lies Gibbs Island where schists, striking N.W.–S.E. at right angles to the trend of the arc, overlie a dunite-serpentine mass very largely altered to a serpentine-schist.

III Discussion—The Geology of the Scotia Sea

The evidence outlined in the preceding paragraphs indicates that South Georgia, Clerke Rock, the South Orkneys, and the Elephant Island group are not normal oceanic islands, but that they all possess sediments or intrusive rocks (or their metamorphic derivatives) indicative of a continental, shelf sea, or geosynclinal environment. Although it is not conclusive, the evidence of the stones dredged near Shag Rock and those obtained near Freezeland Peak (South Sandwich Islands), indicates the presence of a metamorphic basement at these points on the Scotia Ridge. The immensely thick clastic sequence and the acid plutonic rocks in South Georgia, the presence of very coarse conglomerate and current-bedded sandstones in the South Orkneys, and the alpine fold system striking N.–S. across the arc in the *para*-schists of the Basement Complex there, all indicate that these islands belong to a continental mass.

Since the islands are not oceanic they must either represent fragments of a disrupted continental mass or, alternatively, they must be part of a submerged continental mass occupying much of the Scotia Sea area. Continental drift is an attractive hypothesis to apply to the geology of the Falkland Islands which lie only 100 miles to the north of the Scotia Arc (Adie, 1952). Barth and Holmsen (1939, p. 62) have suggested that the islands of the Scotia Arc are fragments of a sialic bridge left behind during the westward drift of Graham Land and South America. If they are fragments of a disrupted mass, then breaks

are to be expected in the submarine ridge connecting the islands. This would be the case both if the arc were a structure formed prior to the disruption of the mass and if it had been formed subsequently to the disruption of the mass by forces acting upon areas of varying crustal structure. The bathymetric chart gives little support to this hypothesis, but one such break may be located between Shag Rock and the Burdwood Bank and there is room for other breaks in the sparsely sounded area between the South Sandwich Islands and the South Orkney Islands.

On the other hand, if there is a submerged continent under the Scotia Sea, it must be associated with a large gravity anomaly. Inspection of the bathymetric chart shows that the average depth of the Scotia Sea is about 3½ km. This is an " intermediate " depth for an oceanic area. The area of the South Pacific west of Drake Passage, and the parts of the Weddell Sea south and east of the South Sandwich Islands and south of the mid-Atlantic ridge, have depths on the average 1,300 to 1,500 m. deeper than the Scotia Sea. However, the forces required to depress and hold down a continental block of a size comparable with the Scotia Sea to a depth of even 3½ km. would be impossibly great unless the mass of the block was radically altered by intrusion or spreading. A similar conclusion has been stated by Officer for the eastern Caribbean (Officer *et al.*, 1957). It may be worth while to consider the similarities and differences between the relatively simple Scotia Arc and the more complex Caribbean arc which connects the Andes and the Rockies through Venezuela and the Antilles. Woodring (1954, p. 730) has concluded on geological grounds that " a considerable part of the Caribbean Sea was land during the Cretaceous, and that at least some of this land was still land during the Eocene ". Naturally, the geological evidence is largely confined to the orogenic islands of the Greater Antilles and the sunken islands referred to by Woodring are mostly placed in the deep but bathymetrically complicated area of the Caribbean south of the Greater Antilles. Moreover, lavas apparently play a more important part in the make up of the Greater Antilles than in South Georgia and the South Orkney Islands. The fold patterns in the Caribbean arc run more or less parallel to the trend of the arc as they do in South Georgia, but in sharp distinction to the South Orkneys where the folds in the older rocks cut across the arc. Seismic work in the eastern Caribbean (Officer *et al.*, 1957) has shown that the bathymetrically rather simple Venezuelan Basin has a structure that is neither oceanic nor yet continental, but is characterized by an unusually low seismic velocity beneath the base of the crust (7·4 as opposed to 8·0 km/sec.) and by a greater thickness of crustal and overlying sedimentary or volcanic material than is observed in normal oceanic sections. The eastern end of the Scotia Sea occupies the

same position with respect to the South Sandwich Islands as the Venezuelan Basin does with respect to the comparable islands of the Lesser Antilles and it may prove to have a similar structure. To extend the analogy further, South Georgia and the South Orkneys may be compared respectively with the eastern islands of the Greater Antilles and with northern central America where highly metamorphosed Cretaceous Sediments have been described (Smith, 1953). Possibly the source of the thick clastic and volcanic sequence in South Georgia should be sought in sunken volcanic islands now represented by the uneven bottom topography south-east of South Georgia (Herdman, 1948, p. 72) and similar to those in the Caribbean south of Puerto Rico postulated by Woodring (1954, Fig. 1).[1] Trendall has shown (1959, p. 9) that the turbidity currents which deposited the volcanic material forming the Cumberland Bay type greywackes came from the south-east and he has postulated the existence during the Mesozoic of a group of volcanic islands, like the present day South Sandwich Islands lying to the south-east of South Georgia and depositing material in an oceanic trench. However, it is difficult to escape the conclusion that the highly metamorphosed Basement Complex of the South Orkneys, folded in flagrant disconformity to the arc, belongs to a continental fragment and was land or shallow sea during part of the Mesozoic when thick marine sediments and tuffs of greywacke facies were accumulating in South Georgia. This continental structure probably terminates south of the islands where the bottom slopes relatively gradually southward towards the deep water of the Weddell Sea and it may be ruptured or down-warped immediately north of the South Orkneys where the slope on the flanks of the 5,000 m. " deep " averages 20°. It is not easy to see how blocks like the parts of the Scotia Ridge near South Georgia and the South Orkneys can have been formed in isolation. Officer and Ewing regard the Venezuelan Basin type of structure as being a stage in the alteration of oceanic to continental structure. The geological evidence suggests the possibility that this process may be operating in reverse in the Scotia Sea although a sufficient mechanism is difficult to envisage. Further seismic work will certainly be easier in the Caribbean than in the stormy Scotia Sea.

IV. Conclusion

Attention has been drawn to the features that distinguish the islands of the Scotia Arc from other oceanic islands. The most noteworthy of these are the presence of thick geosynclinal deposits and granite

[1] Irregularities that could be relics of these volcanic islands south of Puerto Rico can be seen on the seismic profile of the Venezuelan Basin given by Officer (1957, Plate I, profile D).

intrusives near South Georgia and a highly metamorphosed Basement Complex in the South Orkneys from which relatively thick terrestrial deposits were derived during the Mesozoic. It seems probable that South Georgia, the South Orkney Islands, and Elephant and Clarence Islands now have a crustal structure of continental type. There is some evidence of less weight to suggest that a highly metamorphosed basement underlies South Georgia and the volcanic South Sandwich Islands, and that metamorphic rocks of greenschist facies are exposed elsewhere on the Scotia Ridge. If this proves to be true, it would seem probable that there is some crustal thickening under other parts of the Scotia Ridge as well as under the major islands.

Trendall has shown that the bulk of the sediments of South Georgia could have been derived from volcanic islands in an environment similar to that of the South Sandwich Trench at the present day. Trendall's work, and an analogy with Puerto Rico in the Caribbean, suggest that the source of the South Georgian material should probably be sought in sunken islands to the south-east. However, the oldest rocks contain arenaceous fragments which indicate derivation from some other source than a volcanic island and this pre-Mesozoic parent of South Georgia may well have had a continental structure.

The Greywacke-Shale Series of the South Orkneys is similar to the greywackes of South Georgia, for present information indicates that it is composed of the debris of volcanic rocks together with detritus from the weathering of the Basement Complex. The pre-Mesozoic parent of the South Orkney Islands included the Basement Complex and presumably had a more or less continental crustal structure. The shallow water Mesozoic sediments of the Derived Series accumulated in the vicinity of the parent islands which were land during the formation of the conglomerate in the late Mesozoic. Thus a continental fragment seems to have existed in the vicinity of the South Orkneys since the Lower Palaeozoic.

V. Acknowledgments

The writer first became interested in the problems of the Scotia Arc while employed by the Falkland Islands Dependencies Survey in the South Orkney Islands. This paper has been prepared during the tenure of a British Petroleum Company Studentship at Cambridge. He wishes to thank Dr. M. N. Hill of the Department of Geodesy and Geophysics, Cambridge, and Dr. R. J. Adie of the Falkland Islands Dependencies Survey for many suggestions which have resulted in improvements and he is further indebted to Dr. Adie for permission to refer to his unpublished work (Adie, 1953) and for his corrections to Table 1.

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Since this paper was written, two further results have come to hand. First, the preliminary results of 74 seismic refraction profiles in the area have been reported by J. I. and M. Ewing of the Lamont Geological Observatory (American Association for the Advancement of Science, *International Oceanographic Congress, Preprints*, 1959). Most of their results agree with the suggestions made here. They reported a normal oceanic crustal structure under Drake Passage, a sub-crustal velocity of 7·6 km/sec., close south of South Georgia, and crustal thickening beneath the Burdwood Bank and beneath both the Scotia Ridge west of South Georgia and the deeep trough immediately north of it where, unexpectedly, 7 km of sediments have accumulated.

Secondly, a single determination has given the apparent age of mica from the Basement Complex of Signy Island, South Orkney Islands, as 183 million years. The determination was made by the K_{40}: A_{40} method by Mr. D. York, Department of Geology and Mineralogy, Oxford, and by Mr. J. A. Miller, Department of Geophysics, Cambridge. Confirmatory determinations will be reported in due course.

The Bigga House Basic Igneous Complex, New South Wales

By Syed M. Hasan

Abstract

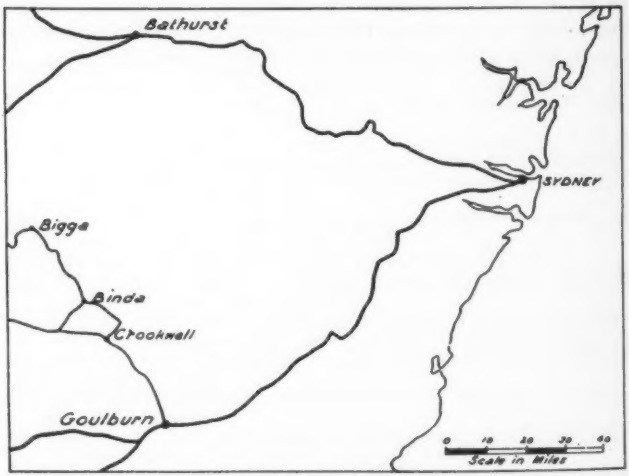
The complex described is composed of basic to ultrabasic rocks, ranging in composition from hornblendites, through meladiorites, to diorites. It is surrounded by the Bigga Granite, which has an intrusive relationship with the basic complex. The nomenclature of these rocks is discussed, and detailed petrographical descriptions, together with modal and chemical data, are given. It is suggested that the original rocks of this complex were probably of gabbroic composition, and that they subsequently assimilated and hybridized to give rise to the observed rock types.

Field Relations

Bigga is situated in the Southern Tableland region of New South Wales and is 60 miles north-west of Goulburn. Text-fig. 1 indicates its geographical position.

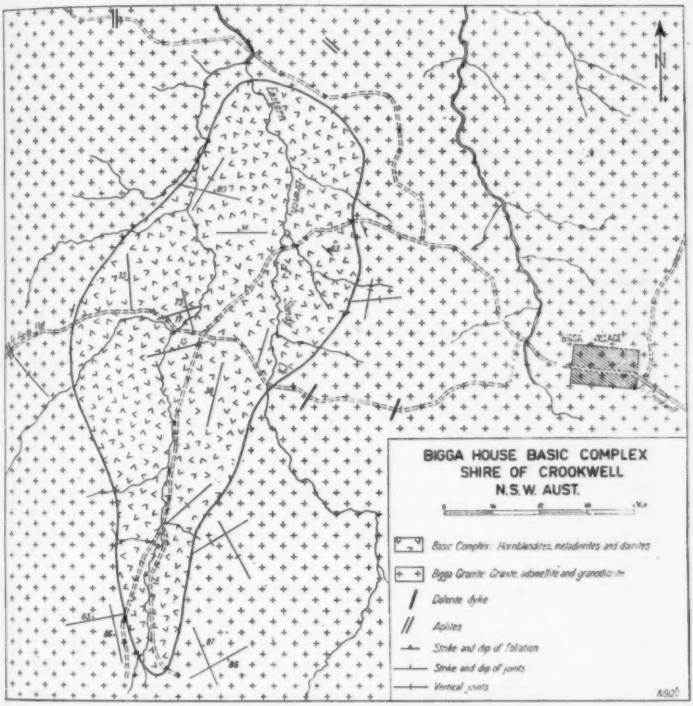
A small mass of basic to ultrabasic igneous rock occurs about 1½ miles west of the village of Bigga. Its maximum length is 3 miles and maximum width 1½ miles; it is rather elliptical in outline and elongated in a north-east–south-west direction.

The Bigga House basic complex, as it is named, is intruded and entirely surrounded by massive Bigga granite (Text-fig. 2). The granite,



Text-fig. 1.—Locality map.

along the contact with the basic rocks, is commonly massive and coarse-grained, but at a few places as, for example, about 2 miles from Bigga by the side of the road (north-eastern corner of the mass), the granite is medium-grained and foliated. Wherever the granite develops



TEXT-FIG. 2.—Bigga House basic igneous complex.

this texture along the contact the foliation follows the boundary of the complex. In addition, there are quite a number of places, such as the junction of the eastern branch of Sandy Creek and the Bigga-Reid's Flat road, where excellent exposures of basic rock are intruded by tongues and veins of granitic rocks. Granite-aplites are also seen, having as inclusions basic rocks of the complex. In the locality mentioned, large crystals of feldspar are scattered throughout the basic rocks. At some places (e.g. on the southern side of Reid's Flat road about 1½ miles from its junction with the road from Grabine), granite is clearly seen to intrude the rocks of the basic complex. As the

rocks of the basic complex are nowhere found in contact with sediments, the above-mentioned relationship is the only direct evidence of their age.

Outcrops of these rocks are fairly good and they occur as tors and boulders, mainly boulders, scattered over the area.

Nomenclature

The rocks occuring in this complex are composed essentially of plagioclase (An_{30-66}), amphibole, pyroxene, and quartz, with minor accessories; the first two make up about 90 per cent of the total and either may be the dominant mineral. Rocks with potash feldspar (as microcline and perthite) and biotite, in addition to hornblende and plagioclase, are also common. Pyroxene is present in small amount.

In the Scottish Highlands, medium to coarse-grained rocks consisting predominantly of green or brown hornblende together with variable amounts of plagioclase, orthoclase, and quartz, have been defined as appinites, the term being introduced by Bailey (1915). Walker (1927) described appinites from Ardsheal Hill with variable mineral proportions and having up to 60 and 70 per cent of greenish-brown amphibole, commonly enclosing well-defined cores of colourless pyroxene. The plagioclase in this case is andesine-labradorite. Other examples are quoted by Anderson (1935 and 1937) from the Scottish Highlands, Deer (1950) from the Glen Tilt Complex, Dean (1938) from Northern Rhodesia, and Nockolds (1940) from the Garabal Hill–Glen Fyne igneous complex. In the first three, two generations of hornblende are seen, but in the last only one generation of hornblende has been noted. Pyroxene is associated with all except the Northern Rhodesian rocks.

In the north-western part of the area under discussion, Stevens (1955) has described from Cocomingla a similar basic complex occurring in the Wyangala bathylith, which is the north-western extension of the Bigga granite. Stevens has used the terms diorite and amphibolite for these rocks. Because of the proximity of the Cocomingla and Bigga House complexes, and the fact that they are intruded by the same granite, it is considered that the terms diorite, meladiorite, and hornblendite are more apt than appinite for this group of rocks. The term amphibolite (used by Stevens) is, in present day petrology, used to name a metamorphic facies, and the writer considers that " hornblendite " is preferable, especially as it is already in use for hornblende-rich melanocratic rocks of igneous origin, and as Stevens does not believe in a metamorphic origin for the Cocomingla rocks.

Having decided the nomenclature for these rocks, a classification in the light of their mineralogy and modal analysis will now be attempted. Rocks having colour index between 10 and 40 are grouped as diorites, between 40 and 70 as meladiorites, and between 70 and 100 as horn-

blendites. According to this classification, out of the eleven rocks analysed modally, seven are grouped as diorites, two as meladiorites, and two as hornblendites.

Petrography

It has not been possible for the writer to map the different types separately because of their random distribution. However, it was noted in the field that only diorite occurs along the granite contact; meladiorites and hornblendites were noticed only away from the granite margin. Granite tongues were seen intruding the basic rocks at quite a number of places and diorites were observed in these localities also.

The diorites, meladiorites, and hornblendites of the Bigga House basic complex are mainly coarse to medium-grained. They range in colour from dark to very dark; some of the quartz-diorites show light colour with the typical black-and-white aspect of diorites, particularly near the contact with the granite, where most feldspathisation of the basic rocks has taken place.

The rocks on the whole are fresh and show beautiful prisms of amphiboles and laths of plagioclase in hand specimen. No preferred orientation of either mineral was noticed. The typical texture as seen under the microscope is either subhedral or anhedral, on occasions porphyritic texture was also noticed. The hornblendites are composed of amphiboles, plagioclase, and a little pyroxene with accessory magnetite, sphene, epidote, zircon, and apatite. The plagioclase in the hornblendites has a composition of An_{60}. In the meladiorites and diorites potash feldspars, quartz and biotite are seen, in addition to amphiboles, plagioclase, and pyroxene; their relative proportions differ from meladiorite to diorite. Chlorite and calcite are also present, the latter being very rare.

Amphiboles.—In all these rocks, except the extreme dioritic end members, the amphiboles are the most important minerals. They may be euhedral prisms varying to anhedral and irregular masses. Commonly two or three crystals occur together with biotite, sphene, and other minor accessories. In places several grains of sphene, occupying angular interspaces between the amphiboles, are in optical continuity. Inclusions of magnetite, plagioclase and potash feldspars are quite common. In places isolated grains of plagioclase in amphiboles occur in optical continuity, giving a sieve structure. Magnetite sometimes show symplectic structure, elsewhere magnetite granules are dusted all over the amphibole prisms.

There are two main varieties of amphibole, one reddish brown, the other olive-green. Both of these may be present in the same slide. Amphibole crystals are usually large and range in size from $0{\cdot}35 \times 0{\cdot}2$ mm. to $1{\cdot}8 \times 0{\cdot}9$ mm. The reddish brown hornblende is more

common in hornblendites than in meladiorites or diorites. In most cases it is partly converted to olive-green amphibole. All stages of alteration are seen, the alteration usually starting from borders, thus leaving a core or central part of reddish brown amphibole. Inclusions of iron ore may follow cleavage traces, giving a type of schiller structure. In places these amphiboles are so dark as to give almost complete absorption, thus making Universal Stage measurements almost impossible. The optical properties of the reddish brown amphibole are given below:—

$(-)2V = 80°–84°$; $\gamma \wedge c = 4°–11°$;
X = pale yellowish brown, Y = brown, Z = deep reddish brown.

The olive-green variety is more common in meladiorites and diorites, and in some thin sections in these rocks only olive-green amphibole, with or without brownish cores, is seen. The following optical properties were obtained for the green amphibole:—

$(-)2V = 40°–41°$; $\gamma \wedge c = 23°–24°$;
X = pale green, Y = green, Z = deep olive-green.

The local replacement by sphene suggests that both amphiboles are rather rich in titanium.

The replacement of amphiboles by biotite does not begin in any set direction. It may start from the border or at an angle to the amphibole cleavage, or in some cases the replacement is parallel to the cleavage in vertical section. Where biotite has replaced amphibole almost completely, isolated grains of amphibole in optical continuity are seen in biotite. Sometimes the biotite lies interstitially, in which case it abuts the euhedral faces of amphiboles or plagioclase and fills angular spaces between them, showing it to be later in the crystallization sequence and not replacing the amphibole.

Pyroxenes.—Most of the pyroxenes have been replaced almost completely by amphiboles, only small cores (between $0{\cdot}2 \times 0{\cdot}1$ mm. and $0{\cdot}45 \times 0{\cdot}28$ mm.) in amphiboles remaining. Both faintly pleochroic hypersthene and colourless to pale green diopsidic augite have been observed. The most striking feature of this amphibole-pyroxene relationship is the structural parallelism between them. Particularly in the vertical sections of the amphiboles containing an irregular core of pyroxene, the amphibole cleavage lies parallel to that of pyroxene, suggesting that the amphibole has replaced the pyroxene.

Biotite.—There are two main types of biotite in these rocks; one with X = pale yellow, Y = yellowish brown, Z = deep brown with a reddish tinge, the other with X = yellow, Y = greenish yellow, and Z = deep greenish brown. Both occur as flakes or in irregular masses, whose size ranges between $0{\cdot}3 \times 0{\cdot}15$ mm. and $1{\cdot}4 \times 0{\cdot}6$ mm. Inclusions of apatite, magnetite, feldspars, and quartz are quite

common. In some cases fine rutile needles give the typical sagenitic structure.

Hall (1941) has established a relationship between the colour of the biotite and the relative proportions of iron, titania, and magnesia. Both these biotites seem to be similar to types which have high FeO with low TiO_2 and MgO. They have replaced the green amphiboles, but as most of the titania of the amphibole was used by sphene, the biotites are therefore rather low in titania.

Plagioclase.—After amphibole, plagioclase is the most abundant mineral. It occurs in euhedral to subhedral laths and tabular crystals and as irregular grains. Size ranges from $0{\cdot}3 \times 0{\cdot}1$ mm. to $2{\cdot}2 \times 0{\cdot}9$ mm. Their composition varies; the range noticed in different rocks of this complex is from An_{30} to An_{66}. Inclusions of quartz, potash feldspars and accessories are quite common. They are mostly fresh, but in some cases have altered to sericite, epidote, or clinozoisite. The alteration always starts from the core of the crystals. Zoning is seen and twin laws noted were albite, pericline, Carlsbad, and albite-Carlsbad, the most common being the albite law. In one or two cases myrmekitic intergrowth was seen, but it is very rare.

The relation with amphiboles has already been discussed.

Potash Feldspars.—Potash feldspars in the form of microcline and microcline-perthite are quite common. They occur in subhedral to euhedral grains, and are often seen enclosed in amphibole or plagioclase, but separate crystals are also common. These are quite large, up to $2{\cdot}7 \times 1{\cdot}8$ mm. Potash feldspar is much more plentiful in meladiorites and diorites than in hornblendites. Microcline-perthite is mainly of the " vein " and " replacement " type (Anderson, 1928). The potash feldspars in general are quite fresh, but in some cases alteration to sericite is noticed. Inclusions of quartz, plagioclase, apatite, and magnetite are seen.

Accessories.—Apatite is quite common as anhedral grains, prisms, and minute needle-like crystals. The latter are seen scattered throughout the slides and in some cases there are literally swarms of them, showing no parallel alignment or preferred orientation. The prisms and some of the anhedral grains are quite large (up to $0{\cdot}8 \times 0{\cdot}2$ mm.).

Sphene is very common and invariably occurs in irregular grains or masses. In a few cases one face may be fully developed. It fills the angular interspaces between feldspars and amphiboles, and also occurs as inclusions in amphiboles. Its textural relation, together with its association with other minerals such as amphiboles and feldspars, clearly show that it is late in the crystallization sequence. Inclusions of magnetite and ilmenite are often seen; these inclusions are always in the central position of the sphene grains. Some irregular masses of sphene are as large as $1{\cdot}2 \times 0{\cdot}45$ mm.

TABLE 1

S. No.	No. of Specimen	Quartz	Potash Feldspar	Plagioclase	Amphiboles	Biotite	Opaque Acces.	Non Opaque Acces.	Colour Index
1	(74)	22·4	16·0	43·1	0·4	10·6	2·7	4·8	19
2	(370)	13·3	16·8	34·5	14·2	15·9	2·6	2·7	35
3	(371)	12·3	18·8	30·7	14·8	19·1	2·5	1·8	38
4	(119)	10·4	24·8	31·3	18·2	11·8	2·4	1·2	34
5	(362)	8·8	0·1	11·3	67·0	—	7·0	5·8	80
6	(307)	8·6	18·6	28·0	20·3	19·2	3·1	2·2	45
7	(108)	8·2	23·6	31·8	23·3	9·9	1·6	2·5	36
8	(151)	8·2	22·6	29·5	20·5	16·8	1·4	0·9	40
9	(131)	7·0	17·9	34·9	22·8	13·2	1·5	2·7	40
10	(75)	1·0	0·7	20·1	70·8	—	4·6	2·8	78

1. Quartz-diorite, about 3 miles north-west of Bigga, on the southern side of Reid's Flat road.
2. Diorite, 4 miles north-west of Bigga in creek bed (Western branch of Sandy Creek) about 1 furlong south of the bridge.
3. Diorite, near No. 2.
4. Diorite, near Bigga House, about 2½ miles north-west of Bigga.
5. Hornblendite, about 3 miles north-west of Bigga. South of Reid's Flat–Bigga road.
6. Meladiorite, near No. 2.
7. Diorite, 1 furlong east of Bigga House.
8. Diorite, just near the junction, western branch of Sandy Creek at the Reid's Flat road.
9. Meladiorite, near No. 8.
10. Hornblendite, about 3 miles north-west of Bigga, south of Reid's Flat road.

Zircon occurs as small crystals, as short, six-sided prisms or as long rods, the latter being up to 0·9 × 0·2 mm. Zircon may give rise to pleochroic haloes in biotite, but this type of occurrence is rather uncommon in these rocks. Magnetite is a very common accessory in these rocks; ilmenite and haematite are not common. Magnetite occurs in irregular grains and large irregular masses; ilmenite as skeletal crystals and occasional translucent red grains of haematite have been observed.

Among the rare accessories is chlorite, which is an alteration product of either biotite or amphibole. In places amphibole has altered directly to chlorite. The chlorite is pleochroic from pale green to dark green and shows rather weak birefringence. Brownish yellow, weakly pleochroic allanite crystals have been observed in a number of thin sections. Some of the larger crystals measure up to 1·1 × 0·3 mm. Calcite is very rare; actually it was observed only in one or two thin sections, filling angular interspaces between the plagioclases.

Modal and Chemical Data

Ten thin sections of the basic rocks were selected for modal analysis, and the results are given in Table 1. In so far as possible, large thin sections were used for all these measurements, and on an average about 456 mm. distance was traversed. The colour index was calculated according to Shand (1949). For the sake of convenience, these results have been arranged according to decreasing quartz content of the rock.

Table 2

Minerals	Diorite	Meladiorite	Hornblendite
Quartz	12·5	7·8	4·9
Potash feldspars	20·4	18·3	0·4
Plagioclase	33·5	31·5	15·7
Amphiboles	15·1	21·5	68·9
Biotite	14·0	16·2	x
Opaque acces.	2·2	2·3	5·8
Non-opaque acces.	2·3	2·4	4·3
Colour Index	34	42	79

Table 2 is compiled from data given in Table 1, and shows the average modal composition of the diorites, meladiorites, and hornblendites of Bigga. It is apparent from this Table that the percentage of quartz, potash feldspar, and plagioclase decreases, whereas the accessories increase from diorite to hornblendite.

Two rocks from the basic complex were selected for analysis, a quartz-diorite (No. 74) and a diorite (No. 370). Modal analyses of these rocks are given in Table 1 (No. 1 and No. 2 respectively.) The

chemical analyses are given in Table 3 together with comparable analyses of similar rocks from New South Wales and Scotland.

TABLE 3

	1.	A.	B.	2.	C.	D.
SiO_2 .	63·45	58·28	55·05	57·00	53·29	57·80
Al_2O_3 .	15·63	18·08	14·15	14·88	8·81	8·76
Fe_2O_3 .	2·31	1·84	1·80	0·68	4·68	3·27
FeO .	2·80	4·06	5·31	7·53	6·66	5·41
MgO .	2·65	3·57	8·07	5·70	9·07	9·80
CaO .	6·07	5·14	9·36	4·97	8·99	8·05
Na_2O .	3·02	4·02	2·82	3·47	3·21	3·02
K_2O .	2·42	2·91	0·72	2·58	1·87	2·01
H_2O+ .	0·90	0·74	1·46	0·54	1·51	0·63
H_2O- .	0·14	0·26	0·22	0·03	0·17	0·13
TiO_2 .	0·50	0·82	0·57	2·15	1·41	0·83
P_2O_5 .	0·45	0·37	0·06	0·85	trace	0·14
MnO .	trace	trace	0·22	trace	—	0·11
CO_2 .	n.d.	nil	0·02	n.d.	nil	n.d.
etc. .	—	—	0·06	—	—	—
	100·34	100·09	99·98	100·38	99·67	99·96

1. Quartz–diorite (spec. no. 74) 3 miles north-west of Bigga, near road on southern side. Anal. S. M. Hasan.
A. Fine-grained quartz-diorite, east of Garabal Hill, Scotland. Anal. W. H. Herdsman (Nockolds, *Q.J.G.S.*, xcvi, 1940, facing p. 510).
B. Diorite, Hillgrove area, N.S.W. Anal. J. G. H. Mingaye. (*Recs. Geol. Surv. N.S.W.*, viii, 1907, 216).
2. Diorite (spec. no. 370), 4 miles north-west of Bigga in creek bed (west branch of Sandy Creek), about 1 furlong south of the bridge. Anal. S. M. Hasan.
C. Hornblendite, Garabal Burn, west of Garabal Farm, Scotland. Anal. W. H. Herdsman (Wyllie and Scott, *Geol. Mag.*, 1913, 540).
D. Quartz-orthoclase Appinite, 700 yards north-east of the head of Allt A'Chama Choire. Anal. W. A. Deer (*Geol. Mag.*, lxxxvii, 1950, 186).

PETROGENESIS

The field evidence, together with evidence from the study of thin sections of these rocks, has already been outlined. The writer was unable to find any rocks representing the " core " of the complex, and thus it remains an open question whether the original rock was homogeneous or otherwise. However, it is quite clear that there is a gradational change in mineralogy from hornblendite to diorite. Regarding the origin of these rocks there are two possibilities: (1) that the basic complex is a sort of " basic front " related to large-scale feldspathisation and granitization of sediments; (2) that the various rock types are due to crystallization (with possibly some differentiation) of an original basic magma followed by invasion of granitic material leading to the hybridization of the basic igneous material.

In recent years the idea of " fronts " has been very popular with petrologists interested in granite and related rocks. The basic complex of Bigga is surrounded on all sides by granite. Nowhere was it found in contact with sediments, although rocks of similar type at " Melrose " and Cocomingla (Stevens, 1955) have invaded sedimentary rocks. But Stevens remarks that " there is, however, no evidence that the basic rocks have been derived from sediments as a by-product of large-scale granitization " (1955, p. 95). Other field evidence, such as absence of xenoliths of sedimentary origin appears to confirm Steven's remark. The " front " idea to account for the origin of the basic rocks of Bigga is far from acceptable to the present writer.

The hornblendites, meladiorites, and diorites show evidence of the discontinuous reaction series of Bowen (1922), with their mineralogical association of orthopyroxene, clinopyroxene, brown amphibole, green amphibole, and biotite. The association of pyroxenes as cores in amphiboles together with calcic plagioclase (labradorite) in hornblendites, suggest that the original material was of gabbroic composition. It is quite probable that the hornblendites are the product of contrasted differentiation of original gabbroic magma, but unfortunately there is no field or chemical evidence to support this suggestion.

Field evidence for large-scale magmatic differentiation is also lacking. The rock types found in the field do not follow any regular pattern; rather, field occurrence is quite haphazard. The pattern of decreasing basicity from the centre of the intrusion towards its margin was never observed. Moreover, one would expect that as differentiation proceeded there would be gradual increase in the proportion of quartz, potash feldspar, and biotite in the rocks, but chemical analysis shows that the potash content of quartz-diorite is rather less than for diorite.

As mentioned earlier, in the field tongues of granite intruding the basic rocks were seen at quite a number of places; excellent examples occur in the creek bed north of the causeway on the western branch of the Sandy Creek, about 4 miles west of Bigga. Here feldspathisation of basic rocks has taken place, and white crystals of feldspars can be seen in the dark basic rocks. Reaction between the granite and the basic rock is evidenced by the fact that the granite (which is essentially a biotite granite) around the complex has developed amphiboles; similarly in the basic rocks of the border zone, biotite and potash feldspars are more abundant. The amphiboles which have developed in the granite at the contact are very similar to those found in the basic rocks, and both brown and green varieties are seen. These amphiboles commonly contain inclusions of feldspars and quartz. In places amphiboles are the chief ferromagnesian minerals in these rocks, instead of the usual biotites. This suggests that hybridization has taken place and the net result is the acidification of the basic

rocks (giving rise to diorites) and slight basification of the granitic rocks.

Age of the Bigga House Basic Complex

Stevens (1955) has observed that at Cocomingla and "Melrose" rocks which are lithologically similar and associated with the same type of granite have invaded Upper Ordovician sediments. As the rocks of this complex are surrounded and intruded by granite, the only direct evidence for their age is therefore that they are pre-granite. The Bigga Granite in turn is of pre-Upper Devonian age.

Acknowledgments

The writer is grateful to Prof. C. E. Marshall for the keen interest he has shown in this work, to Dr. N. C. Stevens for the loan of some thin sections, to Dr. G. A. Joplin, Mr. W. B. Dalwitz, and Mr. B. Morgan for discussion and helpful criticism of the manuscript, and to the technical staff of the Department of Geology of the University of Sydney particularly Mr. E. Armstrong and Mr. D. Hamerstain. For his help in every part of this work, the writer would finally like to express thanks to Dr. T. G. Vallance.

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A Unique Chert Nodule from the Hawes Limestone (Lower Carboniferous, D_1) of Wensleydale, Yorkshire

By D. Moore

Abstract

A unique chert nodule, bowl-shaped, ten feet in diameter and three feet deep, with a mass of crystalline calcite in the bottom, occurs in the lower part of the Hawes Limestone at the base of the Yoredale Series. The overall peculiarities of the nodule require an origin after consolidation of the enclosing work.

Introduction

DURING a recent re-survey of the Yoredale Series of the Lower Carboniferous in their type-area of upper Wensleydale (Moore, 1958), a peculiar chert nodule was discovered in the Hawes Limestone below the *Girvanella* Band. Apart from being the only known occurrence of chert in the Hawes Limestone, it is unique in several other respects.

The nodule occurs on the southern bank of Bardale Beck some distance below the confluence with Ashgill Sike and 400 yards upstream from Marsett Bridge. The exposure lies just to the west of the first wall crossing Bardale Beck above Marsett, its precise location being at the point G.R. 34/897860.

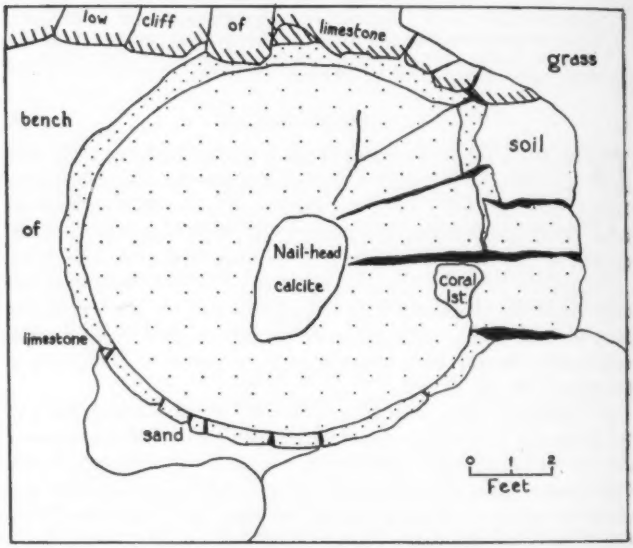
Stratigraphically the chert nodule occurs 27½ feet below the base of the *Girvanella* Band and is therefore within the Lower *Dibunophyllum* Zone of the Lower Carboniferous. It is in the lower half of the Hawes Limestone as defined by the writer (Moore, 1958) and probably only about ten feet above the base of this limestone. The base of the Hawes Limestone is not exposed in Bardale Beck.

Description

The nodule consists of a large bowl-shaped mass of black chert with its underside almost completely enclosed by the massive crinoidal limestone in which it occurs. The bowl is some ten feet in internal diameter and has a depth of about three feet at the centre. The walls are smooth on the inside except for some joint cracks which are most pronounced in the south-west; the slope varies from 30° at the rim to a degree or two in the centre. The outside of the walls, where most clearly seen, is quite irregular, so that the chert ranges in thickness between five and ten inches. At the west side of the nodule the wall swells out into a large boss of chert some two feet square and standing a foot higher than the rest of the nodule (see Text-fig. 1).

In the centre of the bowl is a mass of nail-head calcite—three feet long, two feet wide and varying in thickness from six to fifteen inches.

The individual crystals are one inch in diameter. The nail-head spar extends up the sides of the bowl towards the boss of chert, and near it there is an irregular clot of limestone contained within the wall of the bowl. This limestone contains a colony of *Lithostrotion irregulare* Edwards and Haime. Other colonies of this species of coral occur in the limestone surrounding the chert nodule.



TEXT-FIG. 1.—Plan of chert nodule. Chert dotted, black lines on western side of nodule are large open joints.

The chert is a black, aphanitic chert with sparse small cavities, some of which are lined with amber euhedral fluorite and a vivid green, radially crystalline copper carbonate—probably malachite. In thin section the chert is fine-grained brown chalcedony. Limestone relics on the microscopic scale are not present in the section examined, although the presence of the *Lithostrotion* colony suggests that they should occur.

The upper edge of the bowl is very irregular, even on the southern side where it does not seem to have been much eroded by stream action. On this side, the top of the wall is faithfully followed by a solution plane in the limestone. The plane dies out close to the eastern side of the bowl, but can be followed to the west as far as the limestone is exposed.

Origin

Several alternative modes of origin may be suggested for this nodule. Firstly, it may have been a colossal solid mass of chert which was cut to its present shape by post-glacial stream action. This seems highly unlikely as the chert is strongly jointed and yet there is no modification of the bowl along the joint directions. Furthermore, the nail-head calcite still preserves its crystal faces (and a thick covering of moss) in the presence of rounded boulders as much as two feet in diameter, in spite of its relative softness in comparison with the chert. One may conclude, therefore, that there has been essentially no erosion within the bowl since its uncovering during post-glacial times. It follows that the nodule was formed as it now occurs, at some time between the deposition of the surrounding limestone and the occurrence of the jointing which now disrupts it.

Having decided that the nodule still possesses its original features, it is necessary to determine the precise time of formation of the chert. If, to take the least likely hypothesis first, it originated on the sea-floor as a mass of silica gel, how did the very restricted cavity form, line itself with silica, grow large crystals at its lowest point and yet show no signs of ever having had limsetone within the bowl? Even if all else could be explained satisfactorily, the well-formed calcite crystals would demand the existence of an open void within the limestone. Such a cavity could hardly have developed before consolidation of the overlying rock.

The alternative time of origin for the chert nodule lies between consolidation of the surrounding limestone and formation of the joints which disfigure the nodule. If, as is most likely, the jointing is related to late Carboniferous movements along the Craven Faults, the nodule must be presumed to be of Carboniferous age, formed only a short time after consolidation of the rock. This is the generally accepted period of origin of stylolites (Pettijohn, 1957; p. 213–15 and references therein), one of which (the solution plane mentioned earlier) appears to end at the chert nodule. The unique connection between the solution plane and the chert nodule suggests a common origin. The sequence of events may have been as follows:—

(1) Lithification of a crinoidal calcite mud into massive crinoidal limesone;

(2) Pressure-solution within the limestone caused by increasing thickness of super-imposed sediment.

One particular solution plane developed at its eastern end a large hemispherical cavity, roofed by the upper side of the solution plane and extending downwards for nearly four feet into the limestone beneath.

(3) Silica collected in the cavity and was deposited as a lining to the cavity. The irregular outer face of the chert may reflect original irregularities of the cavity, or be the result of metasomatism of the limestone as it was replaced by the chert.

(4) Following cessation of chert deposition, calcite began to precipitate from the water filling the cavity. The small number and large size of the crystals, as well as their restricted area of growth, imply that crystallization was slow, and took place in tranquil conditions.

Source of the Silica

If we accept a secondary origin for the chert nodule, sources for the silica are reduced to two—disseminated silica within the limestone, either as skeletal remains or as detrital silicates (clay minerals), or hydrothermal solutions of magmatic origin. The lack of other chert in the Hawes Limestone, either along the solution plane or elsewhere, favours an origin from disseminated silica, and does not support an origin from hydrothermal solution.

One may conclude, therefore, that the silica was obtained from solution of silica-bearing debris (both organic and mineral) within the Hawes Limestone. Its most likely time of solution would be at the time of formation of the solution plane at whose end the chert nodule occurs. The reason for the concentration of silica in one place and the peculiar form taken by the concentration are unknown; there is nothing in the nodule itself nor in the surrounding limestone to account for it.

As far as the writer is aware nothing comparable has ever been described. Paramoudras from the Upper Chalk are hollow, but their normal form is cylindrical with the axis disposed vertically (*fide* Chatwin, 1948; p. 35). The largest paramoudras reported are only four feet high and two feet in diameter. Even cherts higher in the Carboniferous, recently described by Wells (1955) and Hey (1956), although very extensive and thick, do not seem to have anything comparable with the Hawes Limestone nodule.

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A Volcanic Vent in the Bogside Mines, Fife[1]

By E. Howel Francis

Abstract

Mines near Culross, in Fife, have traversed a vent of Upper Limestone Group (Namurian) age at levels estimated to be 150 to 250 feet below the contemporary surface. The vent-filling comprises a central basaltic tuff, and a marginal lithic tuff derived entirely from the Carboniferous sedimentary rocks. A sill-like body of lithic tuff has been intruded beyond the vent margins. In sediments outside the vent post-volcanic subsidence has generated small faults; these become flat-lying or undulating where they traverse mudstones and siltstones that are inferred to have been incompletely indurated at the time of the subsidence. The volcanic and post-volcanic processes are discussed in the light of Cloos' interpretation of Swabian volcanism.

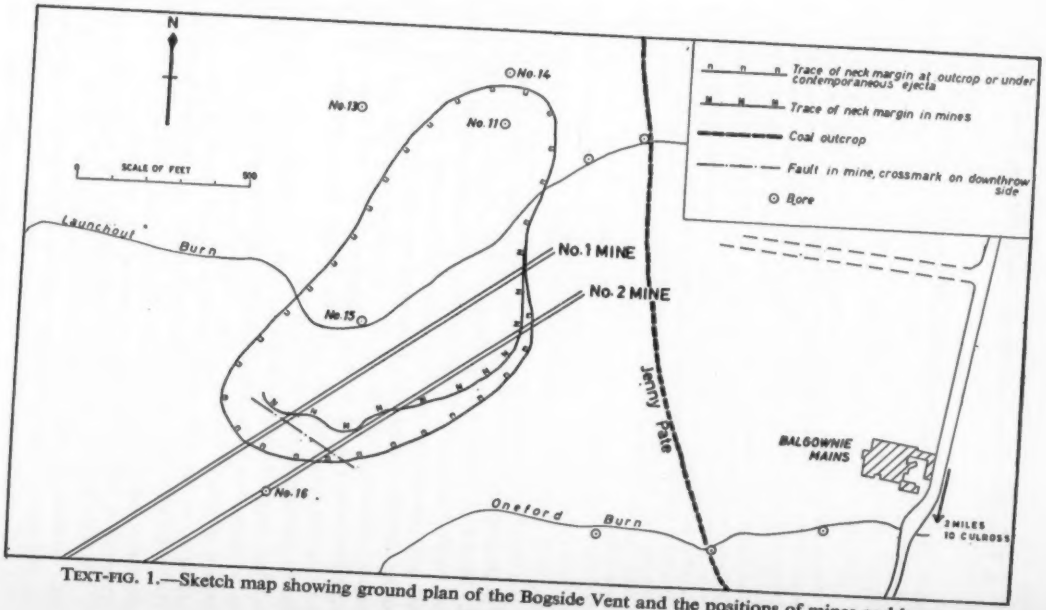
I. Introduction

In the course of exploratory work to prove the Jenny Pate Coal in West Fife several borings (Bogside Nos. 11, 13, 14, 15, and 16), sunk by the National Coal Board during 1956, encountered tuffs which have been interpreted as lying partly within a vent and partly interbedded with the sedimentary succession at a level 240 feet or so above the coal (Francis, 1957, pp. 75–77). This level was therefore taken to mark the surface at the time of formation of the vent and to indicate that the Bogside eruption was one of the latest episodes of Carboniferous volcanism in West Fife.

When, recently, the two Bogside mines were driven from the surface to the Jenny Pate Coal their alignment was determined by the expected pattern of major faulting. The south-western margins of the vent appeared, at the time, to have been located north of the mines in No. 15 Bore (p. 463), but in ground plan the vent proved to be unexpectedly elongated towards the south-west and it was, in consequence, traversed by both mines before the coal was reached.

The mine mouths are situated near Balgownie Mains Farm (Text-fig. 1), about 2 miles north of Culross, and the mines, which are parallel and 150 feet apart, are inclined downwards at a gradient of 1 in 6·6. The Jenny Pate Coal crops out, beneath 10 feet of boulder clay, about 200 feet to the east of the mines which enter rock at

[1] Communicated with the permission of the Director, Geological Survey and Museum.



TEXT-FIG. 1.—Sketch map showing ground plan of the Bogside Vent and the positions of mines and bores.

a stratigraphic level approximately 80 feet higher than the seam. The following is the local succession relevant to this account :—

	Thickness in Feet
Flaggy sandstone	100 to 200
Siltstones passing down to mudstones	50 to 60
CALMY LIMESTONE, in two 3-foot leaves with a 3-foot parting of mudstone	9
Mudstones and siltstones	8 to 15
JENNY PATE COAL	6 to 8
Seatearth, sandy	6
Sandstone	6

II. The Vent Filling

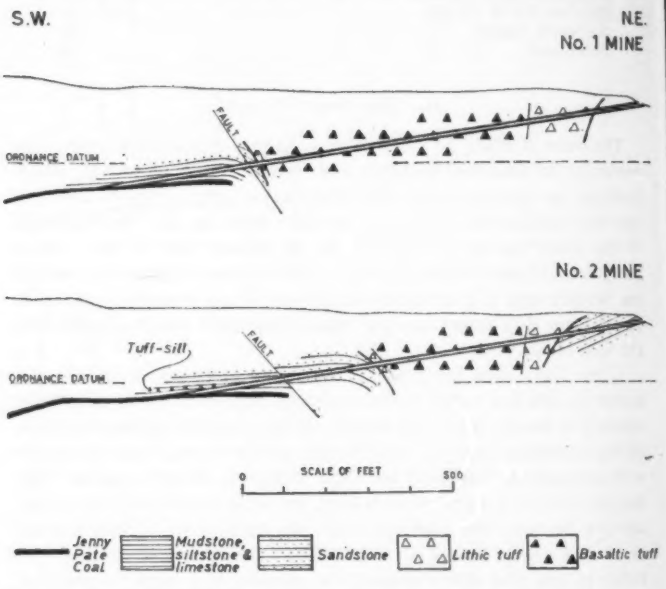
The vent is filled by tuffs of two distinct types which may conveniently be described as lithic and basaltic. The lithic tuff, which contains no igneous debris, forms a narrow outer lining to the vent and the basaltic tuff constitutes the core (Text-fig. 2). The thickness of the outer lining is variable; on the eastern side of the vent it measures 175 and 90 feet in Nos. 1 and 2 mines respectively, but on the western side it is nowhere wider than 10 feet and at one point in No. 2 Mine it is absent and the basaltic tuff there makes contact with the wall of the vent.

Lithic Tuff.—The lithic tuff is dark grey in colour and, with the exception of a few widely scattered specks of green material doubtfully referred to basalt, is formed entirely of comminuted sedimentary rock debris consisting largely of sub-rounded grains of sand—mainly quartz with subordinate fresh and corroded feldspars. These, together with fragments of coal, up to an inch long, are set in a matrix of clay which appears to have been derived from the breakdown of argillaceous rocks and coal. In one slice (S 43553) [1] the matrix is considerably richer in fine coal debris around the margins of a large fragment of coal. The lithic tuff also contains septarian nodules, up to 1 foot in diameter, of dolomite ($\omega = 1{\cdot}68$) which is seen in thin section (S 43182) to have replaced progressively towards the centre of the nodules all the constituent fragments of the tuff except the quartz grains. Towards the vent margins the lithic tuff includes larger fragments of sedimentary rock, notably blocks of sandstone and fragments of coal up to 6 inches long; within 6 to 12 inches of the margins these are orientated parallel to the vent wall and thus appear to be stratified. Traced from the margins towards the centre of the vent the larger fragments disappear and the tuff assumes a more homogeneous and uniform texture.

Basaltic Tuff.—The basaltic tuff has a matrix identical with that of

[1] Numbers preceded by S refer to rock slices in the Geological Survey Scottish collection.

the lithic tuff, but it is distinguished from the latter by a considerable admixture of ragged-edged lapilli, mainly less than an inch in diameter, of pale green basalt most of which are highly vesicular and largely replaced by kaolinite with a little serpentine or chlorite (S 43554). Like the lithic tuff the basaltic rock becomes more uniform in texture when traced inward from its margin. A fragment of a ribbed shell has been obtained from the basaltic tuff in No. 1 Mine. It recalls



TEXT-FIG. 2.—Horizontal sections from south-west to north-east along the lines of the Bogside Mines.

a record of marine shells in the (lithic) tuff filling the East Grange vent, 1½ mile east-north-east of Balgownie Mains (Geikie, 1900, p. 137)—a record that was confirmed in 1958 when a member of a Glasgow Geological Society excursion discovered a shell which, though embedded in the tuff matrix, was nevertheless sufficiently well preserved for Mr. R. B. Wilson to determine it as *Edmondia sp.*

In a few places in both mines the basaltic tuff exhibits planes resembling bedding planes which dip inwards towards the centre of the vent at angles of 10 to 20°. As the texture of the rock is the same on either side of the planes it is inferred that they are merely joints.

Junctions between Lithic and Basaltic Tuffs.—On the eastern side of the vent the junction between the two varieties of tuff is approximately vertical in both mines, but its trace on the sides of the mines is irregular so that, in places, there appear to be pockets and apophyses of one tuff in the other. Where seen in No. 2 Mine this eastern junction is slickensided and there is, at the margin of the basaltic tuff, a marked concentration of basalt lapilli, up to 6 inches in diameter, with veinlets of basalt and calcite. The long axes of some of these lapilli and of a few accidental rock fragments, notably of coal, are orientated parallel to the junction, giving rise to a " stratification " like that seen against the vent margin in the lithic tuff. On the western side of the vent the junction between the two tuffs is inclined towards the centre of the vent at 45 to 70° from the horizontal and is also slickensided, but it is not as irregular a plane as the eastern junction nor is there any sign of " stratification " at the outer edge of the basaltic tuff.

III. Vent Margin

Eastern Margin.—The first 150 feet of No. 1 Mine was walled soon after the mine was begun; it is reported, however, that the vent margin crosses the mine at a point 120 to 130 feet south-west of the mine mouth and that the wall rock of the vent is sandstone. More detailed examination has been possible in No. 2 Mine where, after traversing part of the sandstone which overlies the siltstones and mudstones above the Calmy Limestone, the eastern margin was met 220 feet in from the surface. On the north-west side of the mine the margin is a clean break inclined to south-west, down the mine, at 35 to 40° from the horizontal. The adjacent sandstone dips at a similar angle thus appearing, at first sight, to be concordantly overlain by the tuffs which are themselves " stratified " at the vent margin (p. 459). Polished surfaces of both tuff and sandstone, however, indicate that there has been movement along the junction. The margin obliquely crosses the 11-foot width of the mine and its trace on the south-east side appears as a nearly vertical, but very irregular, line which abruptly truncates the sandstone there dipping down the mine at 20°. For a distance of about 6 feet inside the margin there is a zone of breccia consisting almost entirely of blocks of sandstone which appear to have been derived from the adjacent wall of the vent. The breccia is veined by fine-grained grey tuff which resembles the finer matrix of the lithic tuff. A further irregular, nearly vertical, junction separates the breccia from the main body of lithic tuff inside the vent. This tuff contains large fragments of coal and streaks of pale sandstone aligned parallel to the margin, but within 10 feet these have given way to more normal fine-grained material.

Western Margin.—The western margin of the vent crosses No. 1

Mine at about 45° to the line of the mine and forms a regular plane which dips to north-east, up the mine, at angles of 75 to 90° on the north-west side and 70° on the south-east. The lithic tuff north-east of the plane is about 10 feet wide and is " stratified " parallel to the vent wall—particularly within 6 to 12 inches of it—where there is a " streaking " of white sandstone like that seen at the eastern margin in No. 2 Mine: the effect is accentuated by alignment, parallel to the vent margin, of calcite veinlets in the tuff and wall rock. A 3-foot block of sandstone, identical with the wall rock of the vent, is included within the lithic tuff high up on the south-east side of the mine.

The sandstone forming the wall of the vent overlies the siltstones and mudstones associated with the Calmy Limestone. For a distance of 1 to 3 feet away from the vent margin this sandstone is shattered and veined by fine-grained lithic tuff; it dips in towards the vent at 20 to 35° and is cut off by a fault trending parallel to, and 10 feet away from, the vent margin. The displacement of the fault is down towards the vent, but the amount is uncertain; on its south-western side it brings up mudstones and siltstones which, at the fault, dip towards the vent at angles up to 40°. Within 10 feet of the fault, however, these beds are gently anticlinal and their dip then conforms approximately with the regional dip.

Where the western margin of the vent first appears in No. 2 Mine, 670 feet in from the mouth, it displays a similar structure to that already described in No. 1 Mine. It is a plane which crosses the mine obliquely in an east-west direction (Text-fig. 1) and is inclined towards the vent at 45°. Inside the margin the band of lithic tuff, altogether only 3½ to 4 feet thick, is " stratified " for the first 6 inches. The country rock (sandstone) dips inwards towards the vent at angles increasing across the 11-foot mine from 20° on the south-east side to 35° on the north-west side. For a further 100 feet the strata continue to show a significant increase in dip across the width of the mine: in places the dip reaches 80° on the north-west side. This suggests that the vent margin, after crossing the mine from east to west, turns to run south-west close behind and parallel to the north-western side of the mine as shown on Text-fig. 1. This inference is confirmed, about 800 feet from the mine mouth, by an exposure in a manhole driven into the north-west side, where massive basaltic tuff is revealed just behind the side of the mine and separated from the sediments forming the vent wall by a plane inclined northwards at 50 to 60° from the horizontal. A thin streaky " stratified " alternation of tuff and sandstone separates the massive tuff from the steeply dipping sandstone which is, in places, shattered and veined by lithic tuff. Some of the fracturing takes the form of small-scale faulting heading towards and away from the vent with displacements of the order of 6 inches or less:

faulting of this kind is known around similar tuff-necks in Arizona–New Mexico (Appledorn and Wright, 1957, p. 452) and Swabia (Cloos, 1941, pp. 749–753).

At a distance of 885 feet from the mine mouth the sandstone is cut off by the continuation of the fault described in connection with No. 1 Mine. This throws down towards the vent and brings on first the Calmy Limestone with its adjacent argillaceous beds, then, further down the mine, the Jenny Pate Coal.

It appears from the oblique trends of the vent margin across the mines that the latter have been driven south-east of the maximum width of the vent. In both mines the south-western margin was cut at a level approximating to Ordnance Datum, and was seen to dip to north-east at 45 to 60°. If that dip is maintained the margin should have been cut about 300 to 600 feet below Ordnance Datum in Bogside No. 15 Bore. The bore, however, passed through a high-angled vent margin at about 50 feet below Ordnance Datum; since it is most unlikely that between the mines and the bore the dip of the south-western margin flattens off to about 10° it is supposed that the margin cut in the bore is the north-west margin. The ground plan of the vent drawn from this and other information from bores (Text-fig. 1) thus appears to be irregular and elongated from north-east to south-west. It is of interest to note that the upward flare of the vent, as indicated by observation of its margins, appears to increase as the contemporary surface is approached; thus the western vent margin is inclined at 45° in No. 2 Mine and as much as 70 to 90° in No. 1 Mine, whereas at a slightly higher stratigraphical level, the eastern margin is seen in No. 2 Mine, to dip at angles as low as 35°. This change in the angle of flare compares closely with that observed in Arizonan diatremes (Hack, 1942).

IV. Tuff-Sill

Beyond the fault at 885 feet in No. 2 Mine a discontinuous band of lithic tuff, up to a foot thick, appears 3½ feet above the Jenny Pate Coal among the siltstones and mudstones which separate that seam from the Calmy Limestone. The band is enveloped by a 6-inch layer of crushed mudstone which is laced by an intricate pattern of calcite veinlets. Where it is continuous, the tuff lies concordantly within the sediments which are locally gently folded; where, less commonly, it is discontinuous, some discordance between the tuff and the sediments is discernible indicating transgression of the latter by the former. Since, moreover, the band appears nowhere else at this horizon it is interpreted as intrusive.

These observations supplement the previous record of this tuff in Bogside No. 16 Bore which is intercepted by the mine hereabouts

(Text-fig. 1). In the bore record the tuff was described as resting directly on an unusually thin representative of the Jenny Pate Coal and it was thought at the time (Francis, 1957, p. 77, fig. 3) that the intrusion of the tuff had been the cause of the reduction in thickness of the seam. This reduction, however, is now known to have resulted from low-angled faulting (see below). The faulting and the injection of the tuff together had so crushed the argillaceous rocks between the coal and the sill that they were not represented in the core of the bore.

The tuff is rather paler in colour than the lithic tuff within the vent and is seen in thin section (S 43496) to consist almost entirely of grains of quartz and feldspar, sub-rounded to sub-angular in outline, with subordinate thick flakes of white mica, and very rare fragments of brown, partly isotropic material doubtfully referred to glass. The grains range in size up to 0·5 mm., but by far the greatest number are about 0·2 mm.; this suggests some degree of sorting. The matrix is dark, turbid and obscure and contains a little carbonate; it forms only a small proportion of the rock and is confined to the interstices between the tightly packed grains. This contrasts with the lithic tuff of the vent which is generally softer, less compact and less uniform, even where, well within the vent margins, it is devoid of large fragments.

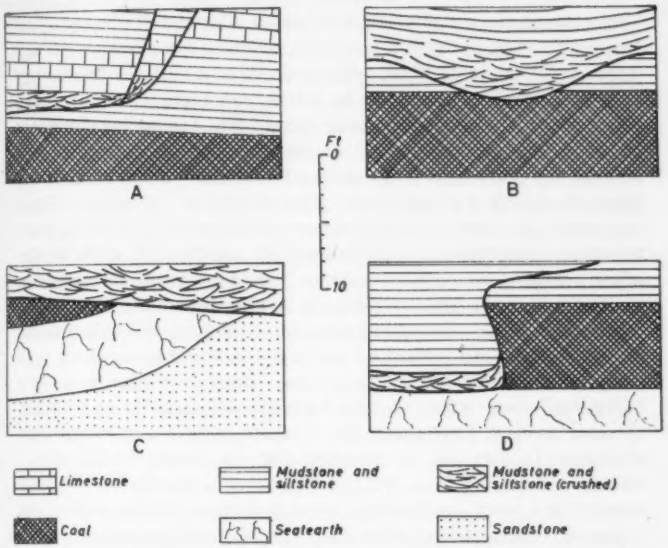
V. Faults

The major fault recorded in the mines and shown on Text-figs. 1 and 2, has the north-west to south-east trend of the regional fault system to which, presumably, it belongs. It seems likely, therefore, that it is Permo–Carboniferous in age. Around the vent, however, there is an unusual pattern of faulting on a smaller scale which is almost certainly a by-product of the volcanism.

The elements of this pattern were well displayed in the face of No. 1 Mine when it had been carried 1,000 feet or so in from the surface (Text-fig. 3*a*). Two fractures having a combined displacement of about 5 feet were there seen to traverse the Calmy Limestone and to coalesce among the mudstones and siltstones below. The plane of the fault was deflected in the argillaceous rocks into an almost horizontal attitude so that the underlying coal remained intact. In most places, however, where such faults have been observed, their flatter components have gouged downwards into the seam thereby reducing its thickness or even cutting it out over distances up to 25 feet (Text-fig. 3*b*, *c*). The process appears to be accentuated, in places, by upward " heaving " of the seatearth underlying the coal. Other flextures of small amplitude occur commonly in association with the faults.

It should be noted that the flat-lying components are always found in the mudstones and siltstones between the coal and the limestone;

there they may form planes of shear, each accompanied by a few inches of crush, or they may express a more general disturbance which fills the argillaceous bed with polished surfaces. The limestone, sandy seatearth and sandstones, in contrast, always appear to show normal fracture. The coal also may fracture normally (Text-fig. 3*d*), but usually it gives way along innumerable small shear planes. Where



TEXT-FIG. 3.—Diagrams to illustrate the effects of small-scale faulting associated with the Bogside volcanism on sediments of contemporaneously differing induration.

hard beds have been exposed and measurement has been possible the largest vertical displacement so far recorded is 15 feet. In the normal course of mining only the flat-lying components of these faults are revealed; calculation of direction and amount of throw of the steeper components is impracticable and it is not even possible to determine whether adjacent " wants " in the coal are caused by the same fault, undulating through the soft beds, or separate fractures. The frequency of such faulting is high near the vent, but scattered examples are still being found at the time of writing up to about 1,500 feet from the vent margins.

It is well known that, where they traverse relatively incompetent argillaceous beds, the hades of faults in Scottish Coalfields are some-

times deflected towards the horizontal. This deflection, however, is localised and on a very small scale and it is believed that the much greater deflection at Bogside was caused by the incomplete compaction of the argillaceous layers when this minor pattern of faults was formed in response to post-volcanic subsidence (*see also* p. 467).

VI. Discussion

In a classic account of Swabian volcanoes, Cloos (1941) distinguished between two types of tuffs which he found filling the central and lower structures of the vents. Tuffs with an orderly, or uniform distribution of their component fragments he called " geordnete Tuffe "; those with a disorderly, or chaotic, distribution of their component fragments he called " ungeordnete Tuffe ". In the " uniform " tuffs fragments of all sizes are distributed fairly uniformly; in the " chaotic " tuffs the larger fragments are distributed quite irregularly. Transition from one type to the other in a single exposure is taken by Cloos to indicate formation of both *in situ*. At Bogside the basaltic tuff at the centre of the vent may be termed " uniform " while the more heterogeneous basaltic tuff at the junction with the lithic tuff is " chaotic ". The distribution of the component fragments of the lithic tuff also changes from " uniform " to " chaotic " as the tuff is traced towards the vent margin. The lithic tuff of the sill-like intrusion is likewise a very " uniform " rock which, like the intrusive tuffs described by Cloos, contains no large fragments. The " stratification " seen in the tuffs at Bogside (p. 462) may be compared with the " chain-stratification " which, in Swabia (Cloos, 1941, p. 721) occurs parallel to the vent margins and also, occasionally, around isolated blocks within the " chaotic " tuffs. Cloos infers that " chain-stratification " has been developed by movement accompanied by friction against the vent walls and around the included blocks, and this friction explains also the slickensiding on the vent walls. The tuff-penetrated breccia with serrated margins in No. 2 Mine (p. 461) also has a parallel in the Swabian tuff-pipes. Cloos (1941, p. 796) tentatively calls this type of breccia " tuffisite " and interprets it as formed by the activity of tuff, made mobile by through-flowing gas, which penetrates the fractures in the country rock; the agitation of the gas against the country rock gives rise to tuff formation, or " tuffisitisation " (*see also* Reynolds, 1951, p. 120).

Following Cloos it is supposed, therefore, that the Bogside vent was formed in a similar manner to those of Swabia: it is envisaged that the upward drilling of the vent was initiated by gas pressure which caused lateral and overhead fracturing of the country rock. The fractures were filled by streams of " active " lithic tuff which, during their passage, incorporated country rock in ever-increasing amounts.

In a broader application Reynolds (1954) has aptly suggested the term " fluidization " to describe the transport of solid particles by a gas-stream.

The presence and inter-relationships of the two distinct tuffs at Bogside require further explanation. Cloos (1941, pp. 728–730) describes a somewhat similar situation where an inner zone of tuff contains twice as many basalt lapilli as an outer zone from which it is separated by a vertical boundary surface. The outer zone is said to be " stratified ", but it would appear from the illustration (op. cit., p. 728, fig. 15) that, as at Bogside, the " stratification " is confined to the outer vent margin. Cloos has not explained the relationship of one tuff to another, but Reynolds has suggested (1951, p. 120; 1954, p. 585) that the inner zone was a region of more rapid flowage of the gas-and-tuff stream, whereas the outer was a relatively stagnant zone of tuff formation. At Bogside the sharp, polished junction between the two tuffs and the repetition, in both tuffs of " chain-stratification " against their outer margins suggest that there are two separate phases of volcanism represented, each with an inner zone of rapid flowage and an outer zone of slower flow caused by friction against the wall rock. During the later volcanic phase the gas-and-tuff stream carried with it fragments of basalt from the underlying magmatic reservoir. This explanation would account also for the irregular marginal distribution of the lithic tuff; the emplacement of the later basaltic tuff caused an eccentric coring-out of lithic tuff.

Some of the conclusions drawn by Cloos are difficult to reconcile with apparently similar evidence at Bogside. The age of the subsidence of the wall-rock, for instance, is thought by Cloos to be mainly contemporaneous with the volcanism, but at Bogside the abrupt inward dip of the sandstone within 20 feet or less of the vent margin is more satisfactorily explained as post-volcanic downward drag of the vent-filling. This view, first propounded by Geikie (1897, p. 73) accords better, too, with the postulated upward pressure of the gas-and-tuff mixture during the volcanism, and it may be significant that in Swabia the only subsidence which can be positively dated is the post-volcanic depression of the bedded tuffs at the tops of the vents.

In other details Cloos' interpretation of the Swabian vents may be inapplicable to Bogside because of differences in the contemporaneous volcanic environments. In Swabia the vents were drilled through a series of Jurassic and Tertiary strata which had an existing fracture pattern that could be used by the volcanic processes. The fractures provided planes to guide the tuff-dyke intrusions (there are no tuff-sills) and also the very large blocks of country rock ready to subside into the gas-and-tuff stream and become incorporated by it. The stratigraphical horizons of the subsided blocks, moreover, can be

accurately determined in Swabia and thus the distance they have moved down or up can be calculated. At Bogside and other Fife localities, however, the lithology of the rock fragments is not diagnostic of any particular part of the local Carboniferous sequence.

It is assumed that, in the present instance, the induration of the country rocks was incomplete to some depth below the contemporary surface, a circumstance that is likely to have been an important factor in the process of tuff formation. It would explain why sandstone fragments are rare and why, even of those just inside the vent margins, many appear to have flowed while, conversely, individual sand grains are among the main constituents of the tuffs. This inference is not invalidated by the brecciation and fracturing of the sandstone forming the vent wall since local induration there is likely to have been caused by the heat of eruption. Argillaceous rocks also are represented in the tuffs only as finely divided material in the matrix. At the time of the volcanism, the mudstones and siltstones adjacent to the Jenny Pate Coal were probably compacted only to the state of stiff clays; this supposition is compatible with the calculated compressibility of muds under a 240-foot load (*see* Skempton, 1944); it is supported also by the evidence of the unusual faulting and by the presence within the " uniform " tuffs of shell-debris divorced from the normal mudstone matrix. The presence of coal fragments within the tuffs, however, as also the fracturing of the Jenny Pate seam by the contemporaneous faulting, may be taken to indicate that even at this comparatively shallow depth below the contemporary surface, the coal had already become fully compacted and indurated.

From the general conditions of sedimentation it seems unlikely that there was, at the time of the volcanism, any existing fracture pattern comparable with that referred to above in the rocks of Swabia. Dyke-like intrusion of early tuffs is likely, therefore, to have been restricted to a few cracks—possibly those opened by preliminary upwards thrust of the volcanism: one tuff-dyke has already been recorded in No. 14 Bore (Francis, 1957, p. 77). The scarcity or absence of vertical fissures may also explain the sill of lithic tuff, which probably formed in response to pressure built up beneath the relatively resistant Calmy Limestone before it was breached by the gas-and-tuff stream of the first eruptive phase.

VII. Acknowledgments

Grateful acknowledgment is made to officials of the National Coal Board at the Alloa Area Office and at Scottish Divisional Headquarters for providing ready access to the mines and to all relevant data. Thanks are especially due to Mr. C. J. C. Ewing, National Coal Board Scottish Divisional Geologist, who accompanied the author on

many visits to the mines and who has made valuable suggestions. The author is indebted also to his colleagues of H.M. Geological Survey for their helpful criticism of the manuscript of this paper.

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H.M. GEOLOGICAL SURVEY,
EDINBURGH.

Monelasmina besti, a new Schizophoriid Brachiopod from the Upper Devonian of Western Canada

By A. E. H. Pedder

(PLATE XVI)

Abstract

Monelasmina, previously known only from the Frasnian of Europe, is described and figured from the Hay River formation (Frasnian) of the Northwest Territories, Canada. The specimens are referred to a new species, *M. besti*.

THE fossils described below were collected by Dr. P. E. Kent of The British Petroleum Company Limited and Dr. E. W. Best, R. L. Pemberton and the writer of Triad Oil Co. Ltd. during a field trip to the Northwest Territories in June, 1958.

The author is much indebted to these companies for permission to publish the work and to present the type specimens to the Geological Survey of Canada.

Systematic Description

Superfamily: DALMANELLACEA Schuchert & Cooper, 1931.
Family: SCHIZOPHORIIDAE Schuchert, 1929.
Genus: *MONELASMINA* Cooper, 1955.

Type species (*original designation*): *Orthis Deshayesii* Bouchard-Chanteraux in Rigaux, 1873, p. 6, pl. 1, figs. 4a–c.

Diagnosis: See Cooper, 1955, pp. 53, 54, but emend third and fourth lines to read: anterior commissure sulcate.

Remarks: The horizon at which *Monelasmina* occurs in the Northwest Territories of Canada, is almost identical with its type horizon in north-west France. In both localities it occurs with *Cyrtospirifer* and species presently referred to *Eleutherokomma* by many Canadians. Both occurrences are several hundred feet above beds with *Stringocephalus* and both are about 200 feet below the main occurrence of the *Cyrtospirifer verneuili* (sensu stricto) and *C. thalattodoxa* species group of brachiopods. Both are Lower Frasnian.

MONELASMINA BESTI Pedder, sp. nov.

Plate XVI, Figs. 1–4c

?1950. *Cariniferella iowensis* Stainbrook? Warren, P. S. & C. R. Stelck (not Stainbrook), *Trans. Roy. Soc. Canada*, ser. 3, xliv, sect. 4, p. 69.

Types: Holotype, specimen originally Triad Oil Co. Ltd. collection

no. X46a, now Geological Survey of Canada, no. 14326. Three paratypes, specimens originally Triad Oil Co. Ltd. collection nos. X46b–d, now Geological Survey of Canada nos. 14327–14329 inclusive.

Horizon: Hay River formation, coquina bed 630 feet below top (Crickmay, 1957, p. 6; not 1953, p. 11); Upper Devonian, Frasnian.

Locality: Canada, Northwest Territories, Hay River, opposite mile 14 of the Grimshaw Road, measured southwestward, about 80 feet above water level and 10 feet below bank top. (Latitude 60° 41′ N., Longitude 115° 54′ W.)

Description: Shell small. Profile unequally biconvex posteriorly, approaching plano-convex anteriorly in adults. Outline subsemicircular; hingeline straight, about 60 per cent of the total shell width in adults and as much as 95 per cent in young specimens; postero-lateral margins sharply rounded, anterior and lateral margins semicircular. Anterior commissure very weakly sulcate. Shell substance thin, calcitic and finely endopunctate.

Pedicle valve gently curved, moderately convex along midline, lateral flanks nearly straight and moderately sloping. Fold very weak and developed only near anterior margin. Umbonal region scarcely differentiated. Beak blunt, projecting and suberect. Beak ridges sharp along entire length. Interarea equilaterally triangular with an apical angle of about 39°. Dental plates obsolete, represented by short, slight ridges on posterior valve floor. Teeth robust, triangular in section. Muscle scar flat, thin, obscuring external ornament, length three-fifths of valve length, outline similar to that of valve.

Brachial valve moderately inflated posteriorly, gently sloping anteriorly and laterally. Sulcus very weak, developed only near anterior margin. Umbo not differentiated. Beak blunt and suberect. Beak ridges sharp along entire length. Interarea equilaterally triangular with an apical angle of about 140°, plane surfaced and apsaclinical. Notothyrium open and with an apical angle of about 85°. Cardinal process small, stout and bifid. Brachiophores large, obliquely directed, situated immediately inside teeth sockets. Median septum high, thin, straight or slightly sinuous and extending from the cardinal process almost to the anterior margin of the valve. Muscle scars subrectangular, impressed, delimited posteriorly by a thickening of the valve floor in the notothyrial cavity, laterally by low parallel ridges, open anteriorly.

Ornamented by fine and very fine, bifurcated and intercalated costae visible on both sides of the valves, except at the muscle scars. Growth lines weak and present only on the interareas.

Dimensions: Holotype (pedicle valve) and paratype no. 1 (brachial valve), length 6·0 and 6·1 mm., width 6·2 and 6·8 mm., depth 2·5 and 0·8 mm.

Remarks: The topotypic horizon is a well-known thin limestone bed

in the Hay River formation (or at the base of it as restricted by Crickmay, 1953, p. 11; 1957, p. 6). The associated fauna is mostly not described and rich, particularly in brachiopods. Some of its elements are: *Nervostrophia* sp., *Productella* sp., *Schizophoria* sp., *Atrypa* sp., *Spinatrypa* sp., *Eleutherokomma reidfordi* Crickmay, *Cyrtospirifer* [*Regelia*] *glaucus* Crickmay and *Cyrtina* sp. Warren and Stelck (1950, p. 69) doubtfully reported the presence of *Cariniferella iowensis* in this bed. Since *Monelasmina besti* is common in it and other shells of similar external appearance are either absent or extremely scarce, it is possible that their specimens are also referable to the new species.

This species is distinguished from *Monelasmina deshayesi* (Bouchard-Chanteraux in Rigaux) by its slightly broader and shorter outline and by its less well developed sulcus in the brachial valve.

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EXPLANATION OF PLATE XVI

Monelasmina besti Pedder sp. nov.

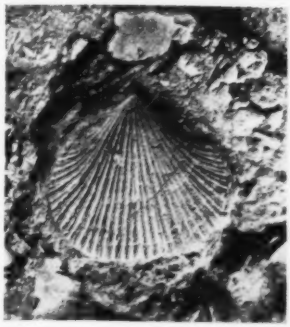
All figures × 4. Specimen numbers refer to the Geological Survey of Canada collection. Photographed by K. S. Wilson.

Fig. 1 — Pedicle valve exterior; Holotype; 14326

Figs. 2a,b — Pedicle valve interior; Paratype 2; 14328

Fig. 3 — Brachial valve exterior; Paratype 1; 14327

Figs. 4a–c — Brachial valve interior; Paratype 3; 14329



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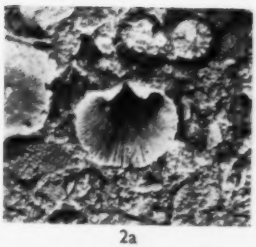

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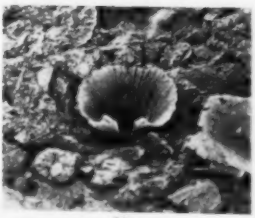

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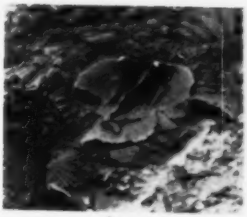

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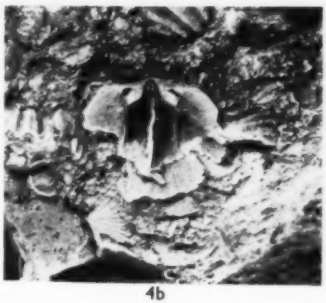

4b

4c

MONELASMINA FROM CANADA.

On certain geological similarities between North-East Shetland and the Jotunheim area of Norway

By Derek Flinn

Abstract

In a recent account of the geology of North-east Shetland (Flinn, 1958, *Quart. Jour. Geol. Soc.*) two nappes of crystalline rocks lying one above the other on a base of meta-sedimentary rocks were recognised. Comparison with the Norwegian geological literature followed by field investigations in Norway has shown many similarities with the Jotunheim area of Norway. In both areas two relatively rigid nappes were thrust one after the other over the surface of the earth to their present positions. In both areas the lower of the two nappes was emplaced first and was subjected to erosion giving rise to sediments which were deposited on the nappes (Phyllite Group of Shetland and the Valdres Sparagmites of Norway). These sedimentary groups had a similar history of formation, deformation, and metamorphism, but differed somewhat in materials because the source rocks were different, although several strikingly similar rock types are present as pebbles in both areas. The remains of the first nappe and the newly deposited sediments were overrun by the second nappe in both areas. The emplacement of these nappes gave rise to considerable deformation and metamorphism in the underlying rocks. If the metamorphic rocks of Shetland are of Caledonian age, as seems likely, then it is possible that the Valdres Sparagmites and the Phyllite Group are stratigraphically equivalent: they are certainly tectonically equivalent.

I. Introduction

In a recent account of the geology of North-east Shetland (Flinn 1958) two nappes of meta-eruptive rocks lying one above the other on a basement of meta-sedimentary rocks were recognised. Comparison with the Norwegian geological literature seemed to indicate that this Shetland nappe pile was similar in many ways to the Jotun nappes in the Jotunheim area of Norway. To investigate these similarities a short time was spent in the field in Norway visiting and collecting in some of the more critical areas. This field work was made possible by a generous grant from the Research Committee of the University of Liverpool.

Outline of the geology of North-east Shetland

In North-east Shetland two nappes of meta-eruptive rocks lie one above the other on an autochthonous basement of meta-sedimentary rocks. The nappes, which vary up to several miles in thickness, appear to be cut from an ultrabasic and basic layered intrusive which had suffered a low grade metamorphism prior to the formation of the nappes. The lower nappe is folded into a north-north-east trending synform, with the upper nappe preserved in its core. The lower nappe

lies on a series of high grade metamorphosed and migmatised sediments which provide no evidence of have been transported by nappe movements, and which were metamorphosed and migmatised before the nappes were emplaced (the first metamorphism).

Above the upper nappe, between the two nappes and between the lower nappe and the basement are zones of highly tectonised metamorphic rocks of various types. These three zones which are called the upper, middle, and lower schuppen zones, contain slices of rocks cut from the basement and from the nappes and some high grade metamorphic rocks not found in the basement. They also contain a series of low grade meta-sediments, the Phyllite Group, derived in part, at least, from the erosion of the lower nappe and deposited almost in their present position on the lower nappe before the upper nappe was emplaced above them.

The schuppen zones were domains of a low grade, tectonising, entirely constructive metamorphism (the second metamorphism) which extended into the nappes and the basement bounding the zones. This metamorphism is considered to have accompanied the emplacement of the nappes because it was centred on the schuppen zones and was of a strongly tectonising nature.

A later metamorphism, the third metamorphism, was dominantly destructive. Its effects are found throughout the area in all rock types, and tectonic units. It may have been caused by late movements of the nappes, or the folding of the nappe pile, or by still later movements.

Outline of the geology of the Jotunheim area of Norway

The part of Norway with which North-east Shetland is to be compared is that part to the east of Bøverdal and Lom, south of Sel and Vågå, and to the west of Gudbrandsdal. It covers the outcrop of the Valdres Sparagmites and includes the Jotunheim mountains and lies at the northern end of the great Sogn folding graben or synform, the core of which is formed by the upper Jotun nappe.

The area is composed of two nappes of metamorphic rocks, the upper and lower Jotun nappes, separated in time and space by the Valdres Sparagmites. These two nappes rest one above the other on a pile of several nappes of rather lightly metamorphosed sediments, which in turn rest on the crystalline basement of the Caledonian mountain chain. This latter pile of nappes together with the crystalline basement are tectonically equivalent to the basement on which the Shetland nappes rest.

The upper nappe and the base of the lower nappe are formed of rocks of the Bergen-Jotun family. They are generally considered to be derived from the sub-Caledonian crystalline basement to the west or north-west of their present position. The upper part of the lower

Jotun nappe consists of Cambro-Ordovician meta-sediments. The lower Jotun nappe rests on Cambro-Ordovician meta-sediments of the same age, but of a facies believed to have been deposited not so far to the west as those forming the top of the nappe. The nappe pile below the Jotun nappes is made up of these Cambro-Ordovician meta-sediments and of Eo-cambrian Sparagmites, both of which were deposited farther west than they are now.

The lower Jotun nappe suffered considerable erosion before the emplacement of the upper nappe. In some places erosion cut through the nappe into the rocks below, and the nappe now seems to be represented by a series of erosional remnants. The Valdres Sparagmites formed, in part, of the erosion products of the lower nappe, were deposited on the erosion surface.

The upper nappe was thrust into position over the Valdres Sparagmites. The emplacement of the upper nappe and of the lower nappe was accompanied by a tectonising metamorphism which was partially constructive and partially destructive, and which was concentrated near the thrust planes.

II. A Comparison of the Tectonic Units of the Two Areas

Although both areas contain two nappes of crystalline rocks, lying one above the other and separated in time and space by a series of orogenic sediments, the rocks of the two areas considered in detail show little similarity.

The *Shetland Nappes* have been cut from a great ultra-basic layered body of normal calc-alkaline type. After the consolidation of the mass and before the nappes were cut from it, it suffered a low grade non-tectonising metamorphism (green schist facies). The upper part of the lower nappe is composed of meta-gabbro, and the lower part of serpentine, with a discontinuous irregular layer of pyroxenite at the contact between the two. The upper part of the serpentine is dunite serpentine which changes downwards through a zone of interbanding to a peridotite serpentine. The upper nappe is composed entirely of peridotite serpentine indistinguishable from that in the lower nappe.

It has not been possible to determine how far the nappes travelled or the direction from which they came. It does seem probable that they travelled to their present positions on thrust planes at, or near, the surface of the earth. Like the lower Jotun nappe, the lower Shetland nappe reached its final position only after much of the sediments deposited in association with its emplacement had been laid down, since slices of the Phyllite Group are found beneath it.

The upper nappe, derived from the same source as the lower nappe, was thrust over it by a route which must have brought it into contact with the structural basement, since it carried with it onto the lower

nappe slices of rocks belonging to the basement. These basement rocks together with slices of the nappes became mixed up with the Phyllite group to form a melange (the middle schuppen zone).

In the *Jotunheim area* the upper Jotun nappe and the base of the lower Jotun nappe are composed of a complex association of plutonic rocks of the Bergen-Jotun family which probably belong to the granulite facies. Rocks present in the nappes are norite, gabbro, anorthosite, Jotun-norite, syenite, mangerite together with relatively small amounts of granite and serpentine. Characteristic of the family are rhombic pyroxene, and anti-perthitic plagioclase, while micro-perthitic potash felspar commonly occurs even in basic rocks.

The lower Jotun nappe is believed to have originated in the Caledonian geosyncline somewhere to the west or north-west of its present position. Since it is composed in part of Cambro-Ordovician sediments of western or geosynclinal facies deposited to the west of rocks of the same age but different facies (mio-geosynclinal facies) underlying the nappe, the nappe must root somewhere to the west or north-west of Bøverdal-Lom (the western limit of the mio-geosynclinal facies) and the minimum distance it has travelled is about 80 km. The upper nappe is believed to have originated somewhere near the source of the lower nappe and has moved a minimum distance of 60 km. from somewhere to the west or north-west of Bøverdal-Lom. It was emplaced after the deposition of the Valdres Sparagmites; in some places it lies on them and in others on the lower nappe or on rocks below the lower nappe. The nappes must have travelled to their present positions over the mio-geosynclinal sediments and the Valdres Sparagmites respectively and therefore on or near the surface of the earth.

Only the base of the lower nappe is formed of Bergen-Jotun rocks. A layer of meta-sediments of the geosynclinal facies of the Cambro-Ordovician sequence rests on the crystallines as an integral part of the nappe. These sediments were apparently deposited on the rocks now forming the base of the lower nappe when it formed the floor of the geosyncline, and remained in place on their base when it was transported as a nappe to its present position. They have been metamorphosed to at least epidote-amphibolite facies and are migmatised in places; they are now mica schists, flags, conglomerates, greenstones and gneisses cut by some trondjemitic intrusions. No rocks tectonically or stratigraphically equivalent to these have been found in Shetland.

The *Norwegian* Valdres Sparagmites which in some places are 500 metres thick are mainly coarse sandstones rich in rather angular clastic grains of quartz and felspar. In many places the sandstones contain grains of the anti-perthitic plagioclase, characteristic of the Bergen-Jotun rocks. Among the coarse sandstones some beds of more

fine-grained sediment occur such as schistose clay sandstones and clay schists. A green sparagmitic sandstone rich in gabbro detritus occurs in the succession, especially near the top. Gabbro conglomerates, which are composed dominantly of well-rounded, to edge-rounded, gabbro pebbles in a matrix of gabbro detritus, also occur mainly at the base of the Valdres Sparagmites. Some of these conglomerates have a normal sparagmitic or even a clay sandstone matrix and very well rounded pebbles of a potash-granite which often contains coarse granophyric intergrowths are characteristic constituents. These pebbles show signs of having been gneissified prior to inclusion in the conglomerate and no source has been found for them. The pebbles in the conglomerate at Dokkvann have been shown to be formed of types of gabbro present in the nearby gabbro masses of Fukhammer and Røsjokollene, which are part of the crystalline base of the lower nappe. Quartzite conglomerate whose chief constituents are rounded pebbles of quartzite, quartz-sandstone and pegmatitic quartz occur mainly in the upper part of the Valdres Sparagmite succession and near the base resting on the Grønsennknipa granite mass, part of the lower nappe's crystalline base. Pebbles of aplitic granite, quartz-porphyry (usually containing both quartz and albite-oligoclase phenocrysts) and granite-porphyry also occur. These pebbles have not been traced to a particular source. The matrix consists of mixtures of sparagmite, clay-schist and in places gabbro detritus.

The erosion of the lower nappe giving rise to these rocks probably started during the emplacement of the nappe and continued after it came to rest. It cut through the nappe into the rocks beneath. The nappe was probably removed altogether in some areas and in others dissected into separate masses. Thus the Røsjokoll, Fukhammer, Espedal, Grønsennknipa, and Heidal masses which are all part of the lower Jotun nappe may not form a continuous sheet.

The Valdres Sparagmites, formed partially of the erosion products of the lower nappe, were deposited on the erosion surface thus produced. In several places, e.g. Espedal and Grønsennknipa, the lower nappe rests on Valdres Sparagmites and must have moved forward over them at some time after they had started to form, either during the main advance of the nappe, or at a later date, possibly when the upper nappe was emplaced. The Valdres Sparagmites are orogenic sediments which may be compared in origin with the alpine flysch and molasse.

The *Phyllite Group* of north-east Shetland has a similar history to the Valdres Sparagmites; it was deposited on an erosion surface on the lower nappe and was derived in part at least from that nappe. It is dominantly composed of finely laminated pelitic phyllites (the Muness Phyllites) together with interbanded graphitic phyllites (the

Norwick Graphitic Schists). In lesser amounts occur sandstones, which vary from coarse felspathitic grits approaching the typical Valdres Sparagmites in appearance, to more pelitic varieties. In close association are found phyllites derived from rocks apparently composed of angular fragments of quartz-albite porphyry, and green schists probably derived by low grade metamorphism from basic igneous rocks which were possibly in part, pillow lavas.

Two types of conglomerate occur in the Phyllite Group. The greenstone conglomerate which is found in several places close to the lower nappe contains pebbles of several types of meta-gabbro some of which can be matched exactly by meta-gabbro from the lower nappe; it also contains scattered spherical pebbles of a coarsely granophyric albite granite. The matrix is composed of large clastic quartz grains and of chlorite, epidote and amphibole derived by low grade metamorphism from gabbro-detritus. The other type of conglomerate is dominantly composed of quartz-albite-porphyry pebbles which often contain phenocrysts of quartz and albite. Associated with these are scattered pebbles of coarsely granophyric albite-granite.

The Funzie conglomerate occurs in the middle schuppen zone with the Phyllite Group but is not interbanded with it. The exposed part of this conglomerate covers an area of several square miles and it has a thickness of several thousand feet. It is mainly composed of quartzite pebbles in a coarse gritty felspathic sandstone matrix similar to the coarse felspathic grits in the Phyllite Group and to the Valdres Sparagmite. In addition to the quartzite pebbles, there are pebbles of granophyric albite granite and quartz-albite-porphyry indistinguishable from those in the Phyllite Group and pebbles of a gneissose biotite-albite-granite, semi-pelitic phyllites and occasional marble. Pebbles of rocks not found elsewhere in the area such as epidote-quartz rocks also occur.

In *Shetland* the structural basement on which the nappe pile lies is formed of fairly high grade (epidote-amphibolite to amphibolite facies) pelitic and semi-pelitic schists and gneisses, quartzites and marbles and calc-silicate rocks together with much amphibolite and hornblende gneiss. This structural basement in Shetland, referred to elsewhere as the " basement " must not be considered the stratigraphical equivalent of the crystalline basement or grunfjellet in Norway.

In *Norway* the structural basement on which the Jotun nappes rest is a further series of nappes which in turn rest on the crystalline basement. These nappes forming the structural basement are composed of Eo-Cambrian Sparagmites and Cambro-ordovician meta-sediments of mio-geosynclinal facies (transitional between the geosynclinal facies of the lower Jotun nappe and of the Trondheim region and the shelf facies of the Oslo region). These rocks are believed

to have been deposited to the east of the geosyncline and therefore to the east of the Cambro-ordovician rocks forming part of the overlying lower Jotun nappe. The highest rocks in the succession are the slates and sandstones of the Mellsenn series (approximately Llandeilan or 4*a* Oslo). Below these are Ordovician phyllites, slates and sandstones, and then Cambrian alum shales, sandstone shales and quartzites, which pass down into Light Sparagmites, the Eocambrian coarse felspathic sandstones. The nappes have suffered a very low grade metamorphism and have slid over each other, and over the basement, from the areas where they were deposited farther west or north-west. The crystalline basement beneath them carries in some places a thin veneer of Cambrian sediments lying undisturbed, where they were originally deposited.

The crystalline basement is exposed in several windows to the south of Bygdin, where it is composed of high grade banded gneisses and amphibolites with some quartzites, and also to the west of Bøverdal, and in the Lomskollen anticline on the north edge of the area. In the latter regions it is composed of granitic and migmatitic gneisses.

III. A Comparison of the Time of Formation of the Nappes

In Norway it is not possible to date the events in the history of the nappes very satisfactorily. It is clear that the lower nappe was emplaced during or after Llandeilan times (4*a* Oslo) since it rests on sediments of approximately that age. It has been claimed that in Bøverdal, and possibly at Mellsenn, the Mellsenn series continues without interruption up into the Valdres Sparagmites. However, it is probable that the lower nappe passed through the Bøverdal area to its present position. Most rock junctions and many levels within the rock units seem to have been planes of movement, so that recognition of a conformable sequence is rather difficult.

The Valdres Sparagmites have been correlated with the Upper Hovin Group and Västerbotten flysch of Upper Ordovician age (Ashgillian) by Vogt (1928, p. 104), with the Upper Hovin Group by Strand (1951, p 35), and with the Middle or Upper Silurian by Goldschmidt (1916, p. 44). Strand (1951, p. 35) correlates the emplacement of the upper Jotun nappe with the unconformity below the Downtonian Old Red Sandstone succession in the region to the north-west. He correlates the folding of the nappe pile to give the Sogn folding graben with the folding of the Devonian succession along the west coast, probably between Middle and Upper Devonian (Strand, 1951, p. 36).

In *Shetland* there is little evidence of the age of either the rocks or the nappes. They are probably both older than the unmetamorphosed Devonian sandstones and conglomerates which unconformably overlie

the metamorphic rocks of Shetland in places. The position of Shetland in relation to Scotland and Norway, and the great differences between its rocks and those of the Lewisian foreland in Scotland, indicate that the metamorphic complex of Shetland is probably of Caledonian age. This is supported by the occurrence in the Mainland of Shetland of spilites, now mostly green schists but in places with recognisable pillow structure, associated with micaceous phyllites (Flinn unpublished work). A similar association is characteristic of the Cambro-ordovician geosynclinal succession in the Trondheim and Bergen areas of Norway. The similarities between North-east Shetland and the Jotunheim area of Norway indicate the possibility that the Phyllite Group is stratigraphically equivalent to the Valdres Sparagmites, it is certainly tectonically equivalent to them.

IV. Conclusions

The basic similarity between North-east Shetland and the Jotunheim area of Norway lies in their tectonic history. All other similarities follow from this. In both areas two relatively rigid nappes were produced one after the other from the same sources and thrust one after the other over the surface of the earth to their present positions. In both areas the lower nappe was emplaced first and due to the resultant relief was subjected to rapid denudation. This gave rise in both areas to sediments similar in history of formation, but differing somewhat in materials because the source rocks were different, although several striking similar rock types are present as pebbles in both areas. In both areas the remains of the first nappe and the newly deposited sediments were over-run by the second nappe which gave rise to deformation and metamorphism of the rocks below it. The grades of the metamorphisms were, however, slightly different, perhaps because the environment of the two areas was different. In Norway the nappes rest on very low grade meta-sediments resting on almost unaltered crystalline floor of the Caledonides on the outside edge of the orogenic belt. Shetland appears to lie deep within an orogenic belt and the nappes rest on high grade meta-sediments and migmatites probably formed in the same mountain building period. If Shetland lies within the Caledonian orogenic belt the Phyllite Group of Shetland may be stratigraphically equivalent to the Valdres Sparagmites of Norway. In both areas the nappe pile was folded into a synform with north-east to north-north-east axis.

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Mesozoic Radiolaria of the Middle East and their Stratigraphical Distribution

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Abstract

Recent work on various Triassic, Jurassic and Cretaceous radiolarian faunas from sections in northern and north-eastern Iraq, all of known stratigraphic horizon, and from elsewhere in the Middle East, confirms the existing view that as absolute indicators of age, without associated evidence, these fossils as commonly preserved are of little use, but that in local and regional problems where they are associated with other evidence they may be of considerable stratigraphical value. The genus *Meyenella* is not regarded as a useful indicator for the Jurassic.

Introduction

THROUGHOUT the Tethyan alpine zone of the Mediterranean countries, central and south-eastern Europe, the Near and Middle East, rocks containing radiolaria are of frequent occurrence. Often they are red and green cherts, associated with serpentines and pillow lavas, and occurring in thrust and shattered zones of relatively complex tectonic history. Since the dating of the component rocks in these zones is of considerable importance for the elucidation of the general geology and associated problems such as oil discovery, the radiolaria visible in thin-sections have received a considerable amount of study. The published notes of A. G. Davis, 1947–1957 (Bibliography in Elliott 1957), mostly fossil-lists in more comprehensive papers by other authors, are from a small portion only of his unpublished work.

The present paper sets out the summarized results of studies on the Mesozoic radiolarian faunas of Kurdistan in Northern Iraq, and is published by permission of the Chief Geologist and Directors of Iraq Petroleum Company Ltd. Much previous work on Middle Eastern radiolaria had been done by comparing the faunas in radiolarites from tectonic zones with those described in the general literature from Europe, Indonesia, and elsewhere. Unfortunately many of these latter localities themselves display radiolarites in tectonic associations, and current views on their age differ from those held when the radiolaria were first described. It was therefore decided that to assess the value of radiolaria for age-determination they should be studied from rocks independently dated, if possible by other fossil evidence and by clear superposition. In Iraqi Kurdistan such radiolarian rocks occur at horizons ranging from Upper Triassic to Cenomanian, and an attempt has been made from them to estimate the stratigraphic utility of these fossils, as they are preserved in the Middle East. In the general literature, despite the profusion of morphological detail available in radio-

laria, they are not on record as having proved very useful as intrinsic stratigraphical markers. Cayeux (1916, p. 383) compared them very unfavourably with the foraminifera in this respect, adding that there was not a single one characteristic of a particular level. Campbell (1954, p. 18) took a more hopeful view of their usefulness, but indicated various factors limiting their utility, at any rate as at present understood.

The view at one time held that siliceous deposits rich in radiolaria indicated old abyssal deposits has been largely discarded, in view of the stratigraphically-improbable conclusions frequently required, and while such deposits may occur, radiolarian deposits of much shallower origin are known. Colom (1958), dealing with old Mesozoic geosynclinal Tethyan deposits in the Mediterranean area, regards the amount of detrital matter present as highly significant, irrespective of the pelagic faunas.

Fossil Radiolaria in the Middle East

In the Middle East, the radiolaria in limestones and calcareous marls are often replaced by calcite, while in the radiolarites they remain siliceous. Apart from occasional pyritization, they are thus usually difficult to isolate, and determinations must be made on thin-sections. The profusion of radiolaria usually present overcomes to a considerable degree the difficulties of determining these three-dimensional surface-detailed creatures in section, since sufficient random diagnostic cuts are available, and thick sections, where not incompatible with translucency or transparency, further permit a useful glimpse of tiny spine and lattice-systems not absolutely in the plane of section. Described species based on these structures often resemble closely other described species from other localities and horizons, differing only in size and detail which one could reasonably suppose to be within normal limits of variation. Moreover, in many of the classic monographs on radiolaria the illustrations have been extensively idealized or restored, as noted by Davis (1950, p. 207). Therefore, rather than stray into subjective evaluation of inaccurate illustrations, when faced with some choice of determination of thin-section radiolaria and hence a tendency to unconscious bias in stratigraphical conclusions, the writer decided to determine distinctive radiolaria at each level generically, with species-numbers where necessary.

The radiolaria studied are from seven different Mesozoic horizons in Northern Iraq, all in the "normally folded zone" of Lees and Richardson (1940). These are (1) Upper Triassic of Ora, Mosul Liwa; (2) Middle Jurassic of Sirwan, Sulemania Liwa; (3) Upper Jurassic (Tithonian) of Chia Gara, Mosul Liwa and (subsurface) Kirkuk Well 109; (4) Valanginian-Hauterivian of Surdash and Sirwan, Sulemania

Liwa; (5) Barremian-Aptian of Sirwan, Sulemania Liwa; (6) Albian of Sirwan, Sulemania Liwa; and (7) Cenomanian of Pir Mugrun, Sulemania Liwa. In the table below the genera determined are followed by their total range, based on Campbell (1954), and then by the numbered Kurdistan horizons, one to seven, in which they have been recognized.

Acanthobotrys	Rec.	4.
Amphibrachium	Dev.–Rec.	4.
Amphimenium	Eoc.–Rec.	5.
Amphistylus	Jur.–Rec.	4,5.
Archicorys	Camb.–Rec.	2, 6.
Axocorys	Jur.–Rec.	6.
Botrypyle	Eoc.–Rec.	3,4.
Cannobotrys	Jur.–Rec.	4,5.
Cenellipsis	Camb.–Rec.	4, 7.
Cenosphaera	Camb.–Rec.	1,2,3,4,5,6,7.
Conchopsis	Rec.	3.
Conosphaera	Jur.–Rec.	3,4,5.
Cryptocapsa	Jur.–Rec.	2,3, 5,6,7.
Dicanthocapsa	Cret.	4.
Dicolocapsa	Camb.–Rec.	2,3,4,5,6,7.
Dictyomitra	Dev.–Rec.	1,2,3,4,5,6,7.
Diplactura	Trias.–Rec.	4.
Dispongotripus	Cret.	4.
Dorysphaera	Ord.–Mioc.	1,2,3, 5,6,7.
Druppastylus	Cret.–Mioc.	5.
Druppula	Palaeoc.–Rec.	2.
Flustrella	Camb.–Rec.	4.
Heliodiscus	Camb.–Rec.	4.
Hexacladus	Mioc.	3.
Hexaconus	Rec.	5.
Hexapyramis	Cret.	7.
Hexastylus	Jur.–Rec.	2.
Lithapium	Camb.–Rec.	4,5,6,7.
Lithatractus	Jur.–Rec.	7.
Lithomitra	Trias.–Rec.	2.
Lophocorys	Jur.–Rec.	2, 7.
Lychnocanium	Cret.–Rec.	6.
Meyenella	Dev.–Cret.	2,3,4,5,6,7.
Palaeacanthus	Jur.	4.
Pentasphaera	Cret.	5.
Phaenocalpis	Eoc.–Rec.	4.
Phyletripes	Jur.	1, 5.

Podocapsa	Jur.	4.
Podocyrtis	Cret.–Rec.	4.
Pterocanium	Jur.–Rec.	5.
Rhopalastrum	Jur.–Rec.	3,4, 6.
Sciadocapsa	Cret.	4,5.
Sethamphora	Jur.–Rec.	7.
Sphaerostylus	Jur.–Rec.	3.
Spongastericus	Jur.–Rec.	3.
Spongostaurus	Jur.–Rec.	4.
Spongotrochus	Ord.–Rec.	2, 4.
Stauralastrum	Eoc.–Rec.	3, 5,6.
Staurodoras	Jur.–Rec.	2, 4,5, 7.
Staurolonche	Camb.–Rec.	1.
Staurosphaera	Ord.–Rec.	3.
Sethocapsa	Camb.–Rec.	6.
Stichocapsa	Dev.–Rec.	1,2, 6,7.
Stichocorys	Trias.–Rec.	2, 4, 6.
Stichopera	Perm.–Rec.	3.
Stichopodium	Rec.	4,5.
Stylosphaera	Dev.–Rec.	1, 5,6,7.
Stylospongia	Dev.–Rec.	4.
Stylostaurus	Ord.–Rec.	4,5,6.
Theocapsa	Dev.–Rec.	6.
Theocyrtis	Cret.–Rec.	1.
Tricolocampe	Jur.–Rec.	1.
Tricolocapsa	Jur.–Rec.	1,2,3,4, 6,7.
Trigonocyclia	Jur.–Rec.	6.
Tripocyclia	Jur.	3,4,5.
Tripodiscium	Jur.	6,7.
Trisphaera	Ord.–Cret.	2.
Xiphostylus	Camb.–Rec.	2,3.

Of these genera 72 per cent show a total range of Palaeozoic–Recent or Mesozoic–Recent (36 per cent in each case), 14 per cent are known elsewhere from Tertiary–Recent (or therein), and 14 per cent are peculiar to the Jurassic–Cretaceous. In view of these figures, mental reservations on uncommon "markers", confined in the Kurdistan sequence to one horizon, are understandable.

Nevertheless, the seven horizons are distinctive one from the other. Although they have many genera in common, as the table reveals, the quantitive assemblages are different in each case, and, with experience, the different suites may readily be distinguished. Unfortunately, comparison with well-dated radiolarian assemblages outside the Kurdistan area is disconcerting.

In Cyprus, a radiolarian development was recorded in the Mamonia formation, dated as Upper Triassic by macrofossils (Henson, Brown and McGinty, 1949, p. 8). Although not clearly seen in relation to under and overlying strata, this evidence was taken as reliable. From the Mamonia, Davis (*op. cit.*, p. 8) determined twelve genera of radiolaria, of which only four are common to the equivalent Kurdistan fauna. Moreover, the appearance of the two faunas is sharply dissimilar. The Kurdistan fauna is dominated by a conspicuous species of *Staurolonche*, a quadrispinous "Star of Bethlehem" radiolarian with inner lattice-work, while the Cyprus fauna, much richer and compared by Davis to the Indonesian Triassic, is something like the assemblage at the Jurassic–Cretaceous boundary in Kurdistan. Yet both these assemblages occur in the central sector of the Tethys at times near enough to be dateable as similar by other fossils, and both lasted long enough, judged by the thickness of beds involved, not to be reflections of transient oceanographic conditions.

In the case of the Kurdistan Cenomanian the radiolarian beds alternate with beds characterized by pelagic foraminifera and other microfossils with a wide horizontal range in the Tethyan area, including northern Italy. The Italian radiolarian beds yield numerous distinctive "Saturnalid" radiolarian, pelagic forms with large and conspicuous encircling rings. These have been figured by several Italian authors, but not one has been seen yet by the writer at the same level in Iraq.

Discussion

The explanation of these anomalies may be due to the fact that radiolaria, mostly planktonic, appear in abundance when marine conditions are suitable. In geosynclinal areas particularly they proliferate in silica-rich waters indirectly due to volcanic action or intrusives: subsequent buckling of the geosynclinal deposits eventually results in a tectonically-complex area showing the familiar association of pillow lavas, serpentines and radiolarites. The radiolarian "bloom" represents a sudden proliferation in favourable conditions of the random population in the area when conditions changed, and this phenomenon seems to have been of general occurrence.

Mutual exclusiveness on the part of radiolaria and other pelagic organisms, so that in successive beds they alternate as majority and minority constituents, may be due to varying marine soluble-silica content over a long period, since the thickness of particular metre-thick beds of very fine pelagic sediment-type is much too great to be accounted for by varying seasonal oceanographic conditions as at the present day. The generic majority-constituents in these separated radiolarian beds vary very much within the same stage (e.g. Cenomanian), apart from the ubiquitous coarse-latticed spherical *Cenosphaera* (? Pre-

Cambrian, Cambrian–Recent). Some thin-section radiolarian cuts determined as *Cenosphaera* may be non-diagnostic circular sections of more varied genera, but it still remains the commonest of all. Frequently a majority within a bed are of about the same size, large or small; between widely different localities or different stages this may mean different species, but between separate alternate lithologically-similar beds in the same formation it probably indicates periodic optimum conditions for growth, or sporadically stimulated proliferation from an arbitrarily-present random size-assemblage. There is always a size-minority.

It is therefore concluded that as absolute indicators of age, without associated evidence, radiolaria as commonly preserved in the Middle East are of very little use. In local and regional problems, however, in association with other evidence, they may be of considerable stratigraphical value, for the different faunas are highly distinctive.

This conclusion is surprising when the amount of fine morphological detail in the radiolarian test, available for classification, is considered. Current text-book accounts state that the skeleton, usually siliceous, is believed to be secreted in the main thickness of the extracapsular protoplasm of the living radiolarian, in the vacuolated layer, flotational in function, termed the calymma. Apparently the skeleton assists in maintaining the calymma extended. Such radiolarian skeletons show an incredible profusion of latticed spheres and other shapes, spine, rod and spicule-systems, and other delicate structures: these are not easy to relate to the internal structure of the soft secreting calymma. Surface-tension probably plays a considerable part in their formation (cf. Thompson, 1917), even if patterning is distinctive for genera and species. The latter are based on the detailed form of the skeleton, i.e. detailed morphology is assumed to be genetically fixed, but there is no absolute proof of this. It is therefore perhaps not wholly surprising that the fossil skeletons show no clear phylogeny apart from a general skeletal elaboration through geological time.

Appendix

Meyenella Davis 1950. Tiny dissociated spicules, regarded by Davis as probably analogous to those of the recent radiolarian *Sphaerozoum*, were described by him as a new genus, *Meyenella*, with three species (Davis, 1950); he also described other spicules as *Palaeacanthus spinosus*. *Meyenella* ranges from Devonian to Upper Cretaceous: according to Davis it increases in abundance to reach a maximum in the Jurassic, and then declines rapidly throughout the Cretaceous. He gave statistical details for its abundance-estimation as an age-indicator, and used it thus as a marker for the Jurassic. Subsequent to this publication, in an unpublished report available to the writer, he recorded it in some

abundance from the Barremian and Cenomanian of Northern Italy: this he accounted for by supposing this area to be a basin in which conditions for radiolaria remained favourable, and from which migration took place as opportunity offered.

During the present investigation *Meyenella* occurred sparingly at all Kurdistan horizons except the Upper Trias, and was sought for especially in the Jurassic. However, the level at which it occurred abundantly was the Valanginian–Hauterivian in the Lower Cretaceous; all three species of *Meyenella*, *Palaeacanthus* sp. and *Sphaerozoum* sp.

The conclusion drawn from this is that *Meyenella* is no more useful than other radiolaria: it abounded sporadically in suitable conditions.

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Cross-Folding in the Gramscatho Beds at Helford River, Cornwall

By J. L. M. Lambert

Abstract

Minor folds in the Gramscatho Beds at the mouth of the Helford River have two predominant trends: W.S.W.–E.N.E., and N.W.–S.E. Main folds on W.S.W.–E.N.E. axes and cross folds on N.W.–S.E. axes have sub-parallel apical planes and occur in alternate zones which trend N.E.–S.W., parallel to the strike of the cleavage. The relations between the two systems of folding suggest that they are virtually synchronous.

It is concluded that the style of folding can be explained by a uni-directional regional stress acting normal to the apical planes of the folds.

I. Introduction

THE Gramscatho Beds are a folded series of clastic sediments exposed along a considerable length of coast in south-west Cornwall. The occurrence of rare plant remains at widespread localities suggests that the series is Middle or Lower Devonian in age. (Hendriks, 1937; Flett, 1946).

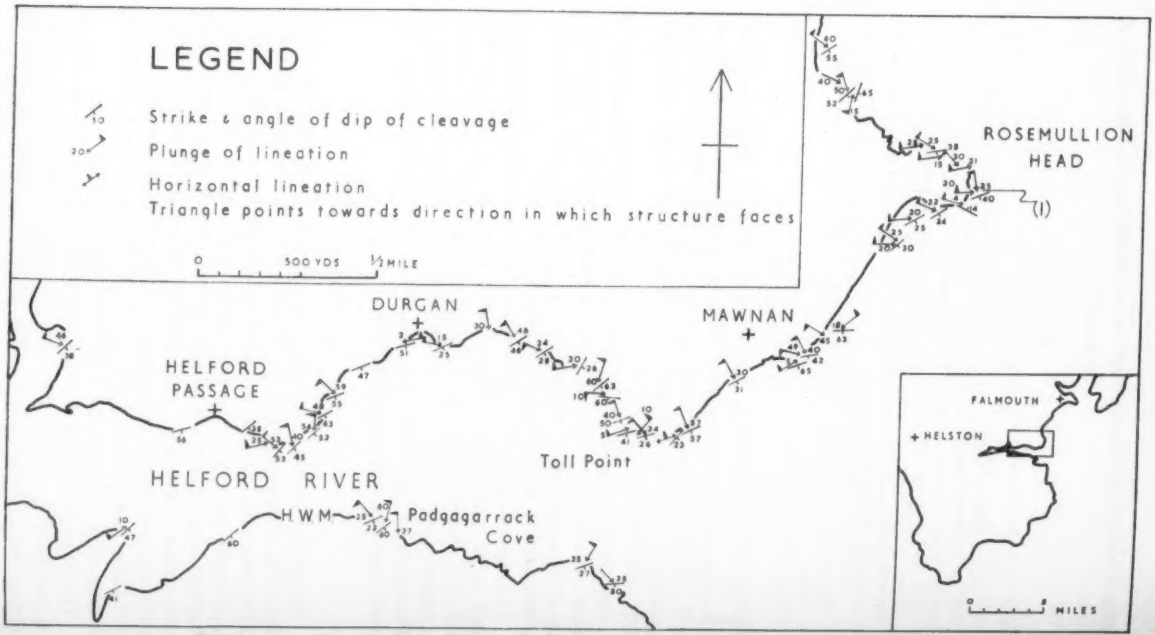
Previous workers (Flett and Hill, 1912; Hill, 1913) recognised the folded nature of the strata, but apart from recording the persistent dip of cleavage and fold limbs to the south-east made no detailed observations of the form and orientation of the folds.

This paper describes the structures in a small section of Gramscatho Beds at the mouth of the Helford River (Text-fig. 1). It is possible, however, that the tectonic style of the structures has a regional significance. Evidence of a similar fold style has been observed at Flushing, near Falmouth, at Portscatho in Gerrans Bay, and on the north coast of Cornwall at Portreath.

II. Lithology

The strata exposed in the area are typical of the Gramscatho Beds. Beds of greywacke, ranging in thickness from a few inches to about 5 feet, alternate with grey and green siltstones and black slates. The argillaceous units are commonly banded and range in thickness from fractions of an inch to a maximum of about 3 feet. Along most of the coast-section arenaceous and argillaceous sediments appear to be present in about equal proportions. However, at Rosemullion Head, Toll Point, and in a small section a quarter of a mile east of Helford Passage, thick (5 feet) beds of greywacke predominate.

The greywackes are fine to medium grained and commonly exhibit graded bedding. In the field this structure is most obvious in the thicker beds, which show a coarse sandy and occasionally a pebbly



TEXT-FIG. 1.—Structural map of the Gramscatho Beds at the mouth of the Helford River.

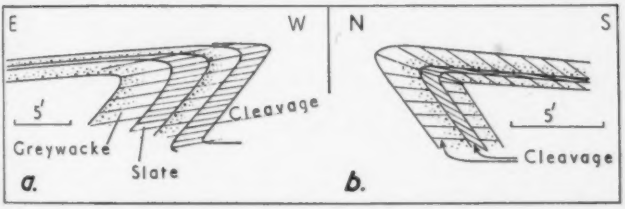
base. This and other sedimentary structures exposed in the area will form the subject of a later study.

III. Structure

The most striking structural feature of the area is the presence of folds with two main trends, W.S.W.–E.N.E. and N.W.–S.E., i.e. approximately at right angles to each other. All the folds are similar in form and scale and are related to a common apical plane cleavage. The following observations regarding cleavage and form apply to the folds on both trends.

Cleavage.

A fracture cleavage is present in both arenaceous and argillaceous



Text-fig. 2.—Diagrammatic profiles of folds. (*a*) Cross fold plunging to the south and facing towards the west. (*b*) Main fold plunging to the east and facing towards the north.

strata. It is replaced by a strain-slip cleavage in the more micaceous argillaceous layers.

The cleavage dip is variable but generally lies between 30° and 50° to the S.S.E. (Text-fig. 3). Cleavage can be observed on all parts of the folds, being equally well developed at fold hinges and on the limbs. It is difficult to detect, however, in those limbs in which cleavage and bedding are sub-parallel. At fold hinges the cleavage lies parallel to the apical plane of the fold. In some folds the cleavage planes are parallel throughout (Text-fig. 2*a*), but when a cleavage fan is present it diverges from fold apices in arenaceous strata and converges towards fold apices in argillaceous strata (Text-fig. 2*b*).

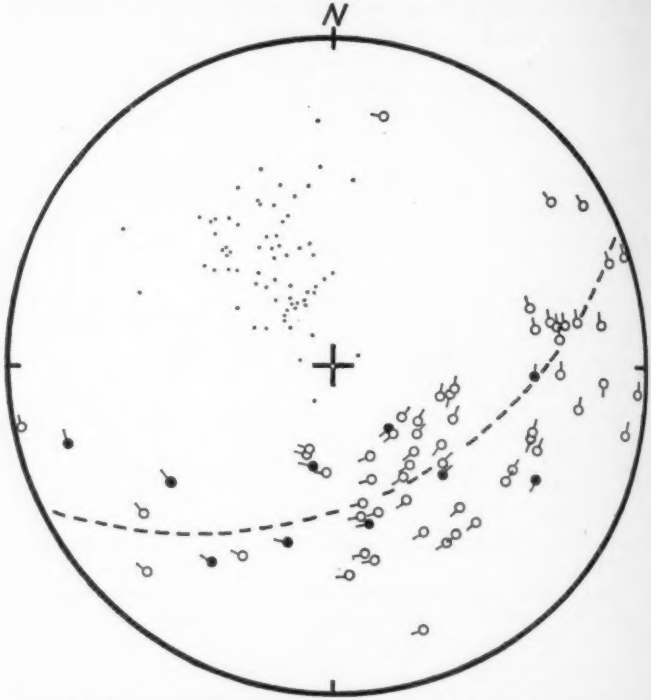
In a small section of coast at Durgan a later vertical cleavage occurs sporadically striking N.E.–S.W. This cleavage is related to minor folds of bedding and crenulations on the apical plane cleavage of the earlier folds.

Folds.

Folds can be seen throughout the section but they are particularly well displayed in the more arenaceous beds.

Text-fig. 1.—Structural map of the Gramscatho Beds at the mouth of the Helford River.

The folds are asymmetrical ; anticlines, in profile, are overturned to recumbent with long upper limbs and short upright or inverted limbs (Text–fig. 2*a*). In the few folds exposed showing both anticlinal and synclinal hinges the range in length of the long limbs is between 50



TEXT-FIG. 3.—Stereographic projection (Wulff net ; lower hemisphere). Dots : poles to cleavage. Open circles : poles of measured cleavage/bedding intersections (data from Text-fig. 1). Filled circles : poles of calculated cleavage/bedding intersections. The bar on each circle is drawn in the direction in which the structure faces. The great circle (dashed line) corresponds to the " modal " cleavage plane.

and 200 feet while the short limbs range from a few inches to 50 feet in length. The folds have the geometry of similar folds and most of them, especially those trending N.W.–S.E., show thinned upper limbs relative to the upright limbs and apical regions. However, a few folds, on both trends, in thick beds of greywacke, are more concentric in shape.

Cleavage/bedding intersections measured at fold hinges lie parallel to the plunge of fold axes. Measured plunges of this lineation and the direction of facing (way up) of the bedding in the plane of the cleavage at each point of measurement are shown in Text-fig. 1.

All the folds are related to a common apical plane cleavage. This relation can be seen in Text-fig. 3, the poles of cleavage/bedding intersections lying about a great circle whose axis corresponds to the "modal" cleavage pole. Two groups of folds, called for convenience main folds and cross folds, can be distinguished. Main folds trend approximately W.S.W.–E.N.E. and plunge at low angles, not more than 25°, to the east and west. Cross folds trend approximately N.W.–S.E. and plunge more steeply, at angles between 25° and 60° to the S.E.

Main folds face predominantly in a northerly direction. Cross folds on the other hand face both (1) towards the S.W., and (2) towards the N.E.

Relations between the Folds.

Some evidence regarding the relations between the folds is provided by their areal distribution. Where the coast runs parallel to the strike of the cleavage, i.e. in a north-easterly direction, both main and cross folds persist when traced along the shore. Thus along some 200 yards of shore, with this N.E. trend, a quarter of a mile east of Helford Passage, only cross folds plunging to the south and facing westward are exposed. A hundred yards east of Toll Point the upper limb of a main fold can be followed along the shore in the direction of the plunge for at least 100 yards. On the shore south of Mawnan some 300 yards of strata, measured at right angles to the strike of the bedding, belong to the inverted limb of a cross fold plunging S.E. and facing S.W.

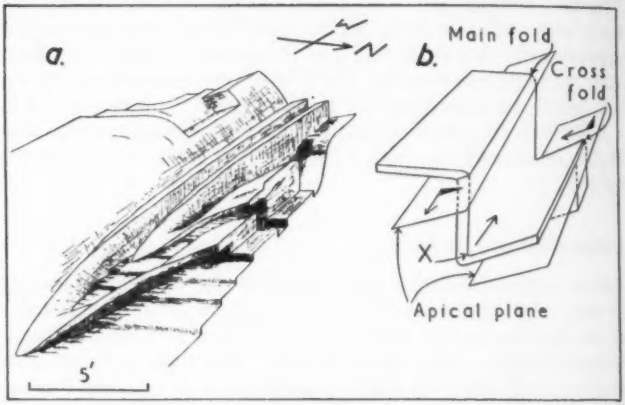
Where the cliffs and shore run approximately at right angles to the strike of the cleavage, i.e. in a north-westerly direction, for example, west of Toll Point and north of Rosemullion Head, main and cross folds occur alternately. The folds occupy small stretches of shore, in some cases less than 30 yards in length.

The evidence thus suggests that main and cross folds occur in alternate zones which trend parallel to the strike of the cleavage and are of small width relative to their length. Within the cross fold zones, at least, it is evident that large thicknesses of strata have been involved in the folding.

Though both main and cross folds, within these zones, show appreciable variations of trend and plunge, there is no indication of a gradual swing of plunge from one axial direction to the other. Adjacent main folds and cross folds generally trend approximately at right angles

to each other. The most frequently observed juxtaposition is that of a main fold facing northwards with a cross fold facing to the west.

Main folds and cross folds occur adjacent to each other, in continuous exposures, at only a few localities. At some of these a fault occurs between the folds, but the fault planes have no apparent preferred orientation. The structural relations of the folds could only be resolved at one locality on the shore at Rosemullion Head (Loc. 1 in



TEXT-FIG. 4.—Adjacent main and cross folds on the shore at Rosemullion Head (Loc. (1) Text-fig. 1). (*a*) Drawing from field sketches and photographs. (*b*) Diagram illustrating the relations between the folds. Plunge symbol as for Text-fig. 1. Main fold trends 87°; plunge 20° E. Cross fold trends 174°; plunge 25° S. Intervening syncline (X) trends E.–W.; plunge 20° (approx.) W. The dip of the apical plane cleavage is between 30° and 40° to the S.E.

Text-fig. 1). Here a cross fold anticlinal hinge is exposed 15 feet to the north of a main fold anticlinal hinge (Text-fig. 4*a*). The relations of the folds are shown diagrammatically in Text-fig. 4*b*. The cleavage in both folds is sub-parallel and dips to the S.E. while their respective axial directions are approximately at right angles. The beds forming the upper limb of the cross fold and the upright limb of the main fold show extreme attenuation in the region of the intervening synclinal hinge. The absence of this common limb at other localities, in which main and cross folds occur adjacent to each other, suggests that attenuation of the limb has, in most cases, proceeded to rupture.

IV. CONCLUSIONS

The strata exposed in the area have been folded on two dominant axial directions. Main folds trend approximately W.S.W.–E.N.E.,

cross folds trend approximately N.W.–S.E. All the folds are related to an apical plane cleavage which dips generally towards the S.E. A variation in cleavage dip is indicated in Text-figs. 1 and 3. This may be due to faulting but is more probably due to divergence and convergence of cleavage on fold limbs.

It is concluded from the evidence in the field that the two sets of folds are of essentially synchronous formation. There is no evidence of refolding of cleavage and indeed at the one locality where adjacent main and cross folds can be observed in continuous beds the cleavage planes are essentially parallel throughout the exposure. The folds at this locality must be interpreted as synchronous as neither fold axis has been folded by the other.

The structural relations of these folds are comparable, in certain respects, to the structural relations of the Caledonoid and cross folds described from the Dalradian and Moinian groups of Scotland. Thus in the Central Highlands (King and Rast, 1956*a*) Caledonoid folds trending N.E.–S.W. and cross folds trending N.W.–S.E. can be observed on all scales. Though Caledonoid and cross folds occur together at certain localities in the same exposure and even the same hand specimen, small scale and major cross folds occur alone in well defined belts of country trending N.W.–S.E. In the Ben Vrackie area the small-scale cross-folds " always plunge in the general direction of dip which is determined by the Caledonoid folding " (King and Rast, 1956*a*, p. 263). The authors conclude that the two systems of folding were developed effectively simultaneously.

In the Cowal area (King and Rast, 1956*b*) recumbent folds on N.E.–S.W. (Caledonoid) axes and N.W.–S.E. (cross-fold) axes, with apparently coincident axial planes, represent the first episode of deformation. These folds are again interpreted as being of essentially simultaneous formation.

In the Helford River area the distribution of the folds suggests that main folds and cross folds occur in alternate zones which trend parallel to the strike of cleavage. The general correspondence of all folds in form and scale indicates that the relationship between stress and strain is similar in both main and cross folds.

The close connection between cleavage and folds suggests that they are genetically related. Thickness-variations of the beds in the folds correspond to the variations in the angle between cleavage and bedding. This relationship could be interpreted as indicating that the cleavage-planes have acted as planes of slip (Gair, 1950). However, as the geometry of the folds can be satisfied by inferring shearing parallel to the fold directrices (Hills, 1953, p. 84) or direct compression acting normal to the apical planes of the folds, the possibility of shortening normal to the cleavage cannot be excluded.

If shearing is admitted as the primary stress during the stage of deformation represented by the folds, it would follow that the stresses acted approximately at right angles to each other in main fold and cross fold zones. It is, however, difficult to relate this stress distribution to a uni-directional regional stress.

If, on the other hand, the primary stress is regarded as acting normal to the apical planes of the folds the orientation of this stress would coincide in main fold and cross fold zones. A regional stress acting normal to the apical planes of the folds can therefore be inferred. It is thus necessary also to infer that main and cross folds had developed as flexures before the imposition of cleavage in the earlier elastic stage of deformation.

The writer wishes to thank Mr. M. Stone and Mr. T. G. Miller for valuable discussion and criticism during the preparation of this paper. The field work was undertaken with the aid of a grant from the research fund of the University College of North Staffordshire.

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The Term Eucrite

By M. J. Le Bas

Abstract

An account is given of the history of the term " eucrite ". It is shown to be very varied and hence has been a source of confusion to authors wishing to employ the word with precision, and to readers trying to understand its exact meaning. Because of the lack of agreement over the interpretation of this word, the author proposes that its use should be discontinued and the term " gabbro " utilized in its place.

Introduction

THE study of the gabbroic rocks of Carlingford and other Tertiary complexes has revealed several interpretations of the term " eucrite ", since its introduction nearly 100 years ago. Many of these are contradictory and originated by the incorrect and incomplete description of a rock which was later taken as the type specimen for " eucrite ". The following is a fairly comprehensive account of the definitions of this term.

History of Nomenclature

The term " eukrite " was introduced by Rose in 1863 in his reclassification of meteorites. He derived the name from a Greek word meaning " easily distinguished " because he thought (p. 29) " eukrites " could be recognised without difficulty on account of their appearance and distinctive constituents. He defined them as being associations of augite and anorthite with accessory pyrrhotite, nickeliferous iron and olivine. His type examples were the meteorites from Juvenas, Stannerm, Jonzac, and Petersburg. Cotta (1866, p. 149) and Tröger (1935, p. 158) imply that the term " eukrite " was used earlier, by Rose in 1835, Genth in 1848, and Haughton in 1856. This, however, is not the case. The three latter authors merely described certain rocks which were later defined as " eukrite ".

On comparing meteoritic " eukrites " and terrestial rocks, Rose (1863, p. 144) found that the rock analysed and described by Haughton (1856, p. 197) from Grange Irish, Carlingford, fitted his definition of " eukrite ". Haughton (p. 196) had identified the constituents as " anorthite " and " hornblende ", but Rose showed the " hornblende " in fact to be augite. Rose further said that the " hypersthenfels " of the Isle of Skye was also " eukrite ". He distinguished between the meteoritic and terrestial " eukrite " by the presence of native iron in the former and the coarse grained character of the latter (p. 145).

Haughton (1856, p. 193) had named his " anorthite " and " hornblende " rock " syenite " and had applied that term to the majority

of the basic rocks of Carlingford no matter whether they were dykes or larger scale intrusives. The present author has visited the Grange Irish locality following Haughton's description. The "syenite" analysed would be better described in modern language, as a medium grained porphyritic dolerite cone-sheet cutting Carboniferous Limestone, whilst the "syenite" of Carlingford Mountain is a large intrusion of gabbro. Haughton analysed the plagioclase which formed over half his Grange Irish "syenite" and found it to be pure anorthite. Un-

TABLE 1

	A.	B.
SiO_2	48·49	47·52
TiO_2	0·79	—
Al_2O_3	22·41	28·56
Fe_2O_3	2·63	7·23*
FeO	4·97	
MnO	0·11	—
MgO	4·27	1·48
CaO	12·32	15·44
Na_2O	2·48	—
K_2O	0·48	—
H_2O+	1·08	—
H_2O-	0·18	—
P_2O_5	0·05	—
	100·26	100·23

* Total iron as Fe_2O_3

Norm of A.	
Orthoclase	2·78
Albite	20·96
Anorthite	48·65
$CaSiO_3$	5·22
$MgSiO_3$	8·80
$FeSiO_3$	4·76
Mg_2SiO_4	1·26
Fe_2SiO_4	0·92
Magnetite	3·71
Ilmenite	1·52

Mode of A.	per cent
Plagioclase (as phenocrysts)	57
Plagioclase (in groundmass)	12
Clino-pyroxene	13
Uralite	16
Iron-ore	2

A. Porphyritic dolerite from centre of cone-sheet 15 feet thick, E.S.E. of Slieve Foye, Carlingford at 800 feet O.D. Analyst M. J. Le Bas.
B. "Syenite" (later defined as "eucrite") from Grange Irish, Carlingford. Analyst S. Haughton (1856, p. 197).

fortunately for subsequent geologists, Haughton did not determine the soda content, but only that of silica, alumina, lime, and magnesia, and hence could not come to any conclusion but that it was pure anorthite. The present author's determination of the composition of this plagioclase, using refractive indices, gives a variation from core to margin of 87 to 55 per cent molecular anorthite content.

Haughton's analysis of the Grange Irish "syenite" has often been quoted (e.g. Harker, 1908, and Johannsen, 1937) as being that of the type "eucrite". This is compared in Table 1 with the chemical analysis of a medium grained porphyritic dolerite cone-sheet which appears to be similar in all respect to Haughton's Grange Irish rock except for the fact that it occurs in another cone-sheet a mile from Grange Irish. In thin section, both these rocks show two generations of plagioclase; bytownite (zoned to labradorite) phenocrysts, and labradorite laths in the groundmass. Both rocks contain colourless to pale brown, partially altered, ophitic augite, and some skeletal iron-ore.

No olivine, biotite, quartz, or potash-feldspar has been observed in either. It is suggested that analysis A (Table 1) gives a better picture of the rock under discussion.

In 1866, Cotta applied " eukrite " to terrestial rocks and described it as " a crystalline-granular compound of anorthite and augite, occasionally with some olivine, hornblende, and epidote " (p. 148). Zirkel defined it (1866, p. 135) as a rock consisting of anorthite and augite only. He took as his type specimen the Grange Irish rock which Cotta had also quoted.

Lasaulx considered " eukrite ", both terrestial and meteoritic, to be an association of anorthite and augite in variable proportions (1875, pp. 316 and 471) and applied it to the " syenite " analysed by Haughton. But in 1878, after a detailed study of the basic rocks of Carlingford Mountain, he distinguished between " eukrites " and " gabbros " by the former containing augite and the latter diallage. He further said that the feldspar was to be labradorite or anorthite in both cases (the term bytownite was not commonly used at that time) and that both could contain olivine (p. 433). Lasaulx, in this way, reclassified Haughton's " syenite " as olivine-gabbro (p. 429). However, he did not make it clear whether he would still consider the particular " syenite " analysed by Haughton to be " eukrite " or not, as he did not mention Grange Irish though he quoted Haughton's analysis. It would appear that he failed to realise that the rocks of Carlingford Mountain and those of Grange Irish are quite distinct. Haughton certainly thought the two were identical (1856, p. 193) as did many subsequent authors.

Traill, of the Irish Geological Survey, variously described these rocks as gabbros and dolerites (1878, p. 13) but did not use the word " eukrite ".

Tschermak considered " eukrite " to be an association of lime-poor diopsidic pyroxene and pure anorthite (1885, pp. 465 and 579). He applied the term to both terrestial and meteoritic rocks quoting the Juvenas meteorite.

Dana defined " eucryte " as a " doleryte-like rock, consisting chiefly of anorthite and augite, with sometimes chrysolite " (1887, p. 486). He mentions the occurrence of this rock at Carlingford.

Teall was the first to spell it " eucrite " (188, p. 134) and quoted Rose, Zirkel, Haughton, and Lasaulx as above.

In 1894, Sollas described the rocks of Slieve Foye (Carlingford Mountain) as gabbros, and found the contained plagioclase to be bytownite (pp. 482–4). He did, however, (p. 484) cite Haughton's anorthite chemical analysis and spoke of the containing rock as " eucrite ".

Harker did not call any of his Skye rocks " eucrite " but in Rhum

he applied the term to rocks containing bytownite or anorthite as the plagioclase, a " richness in olivine and a very general association of rhombic pyroxene with the monoclinic " (1908, p. 93). Then he stated (p. 97) that the only " eucrite " proper in the British Tertiary districts " is that of Carlingford " and quoted (p. 98) Haughton's 1856 analysis. Harker emphasized the role of rhombic pyroxene in " eucrite ".

Iddings (1909, p. 376) defined " eucrite " as a " gabbro whose calcic feldspar is anorthite ".

To H. H. Thomas working in Mull, " eucrite " " is characterized, usually, by an abundance of olivine, and by the presence of an ophitic diallagic or normal augite and of a feldspar near bytownite in composition " (Bailey, 1924, p. 250). The basicity of the plagioclase was one of the main features of " eucrite " in distinguishing it from normal gabbro.

Richey, in his account of the Ardnamurchan rocks, extended Thomas's interpretation to include labradorite in the range of the plagioclase for " eucrite " (1930, pp. 267, 305–6, 324, and 327). In 1948, however, Richey stated (p. 53) " eucrites " to be " gabbroic rocks with basic plagioclase feldspar (bytownite or anorthite) ".

When Tröger (1935, p. 158) considered the term " eucrite ", he placed it in the family of gabbros. He described it as typically containing 48 per cent plagioclase (An_{88}), 40 per cent clino- and ortho-pyroxene, 9 per cent olivine, and 3 per cent iron-ore with or without biotite. He gave (p. 154) the composition range of plagioclase for " eucrite " as An_{75-95}.

In Johannsen's classification of rocks, " eucrite " is re-defined as containing anorthite and augite (1937, p. 347), thus reverting to its original sense. Haughton's " syenite " is quoted by Johannsen as the type " eucrite ".

Shand stated (1949, p. 436) that " the name ' eucrite ' is sometimes given to gabbros in which the feldspar approaches pure anorthite in composition ".

" Eucrites " are described by Williams, Turner, and Gilbert as " characterized by extremely calcic feldspar—namely, bytownite or anorthite. Augite is their chief mafic mineral, hypersthene is almost always present, and most varieties carry abundant olivine " (1954, p. 52).

In a critical discussion on the nomenclature of the ultrabasic rocks of Rhum, Brown (1956, p. 12) uses " eucrite " for gabbroic rocks containing bytownite feldspar. He considers (p. 12) the term useful since it can be used in the distinction between the allivalites with ultrabasic affinities and eucrites with basic affinities. However, when describing the bytownite-gabbro from Barkeval (p. 41) which " shows more marked affinities with the ultrabasic rocks than do the other

gabbros" of Rhum, he terms it "a 'eucrite' on the basis of its composition, though the name obscures, to some extent, its true genetic relationship". It appears to the present author that Brown's use of the word "eucrite" complicates rather than clarifies the distinctions and kinships between the various basic rocks of Rhum.

The interpretation of the word "eucrite" has been less varied when applied to meteorites than to terrestial rocks. Merrill defined "eukrite" as "consisting essentially of augite and anorthite with a little iron sulphide, structure basaltic" (1916, p. 2). More recently, the constituents of meteoritic "eucrite" have been given as anorthite and clino-pyroxene (Prior, 1953, p.x). Both quote the Juvenas meteorite as being "eucrite". But Game, when working on the plagioclasse from the Juvenas "eucrite" (1957) has found that the feldspar ranges in composition from An_{85} to An_{88}.

Conclusions

In the opinion of the author, there appears to be little in favour of the retention of the term "eucrite" as used for terrestial rocks for the following reasons:—

(1) A term with such a varied history as given above cannot be of use in an accurate and well defined terminology.
(2) The term has been little used by geologists over the whole world, being, on the whole, only used in connection with the British Tertiary Province.
(3) "Eucrites", in the original sense of being anorthite-augite rocks, are very rare and most rocks once defined as "eucrite" are now found to fall outside the scope of the original definition.
(4) There is a lack of close correspondence between meteoritic and terrestial "eucrites".
(5) All "eucritic" rocks lie within the field of gabbros.

Thus the author proposes that in place of the term "eucrite" for certain terrestial rocks, that of "gabbro" be employed with or without suitable prefixes as may be applicable in any particular case.

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DEPARTMENT OF MINERALOGY AND PETROLOGY,
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A Note on the Nosean Phonolite of the Wolf Rock, Cornwall

By C. E. Tilley

THE first systematic descriptions of the nosean phonolite of the Wolf Rock were given by Allport (*Geol. Mag.*, 1871, p. 247; 1874, p. 462). Later a fuller account of the rock was provided by Teall in his *British Petrography* (1888, pp. 367–368). Since that time the rock has been repeatedly figured in text-books of petrography and in the light of two chemical analyses provided by J. A. Phillips (in Allport, 1871), regarded as a type example of a more sodic phonolite chemically comparable with the plutonic mariupolite. In view of the early date of these analyses, Mr. J. H. Scoon has at my request carried out a new analysis of the fresh rock, the results of which are provided in Table 1 (No. 1). This analysis reveals significant differences from the original, particularly in the potash content and shows that the rock is to be compared with the well-known phonolite of Brüx, Bohemia (Table 1, No. 3), and a phonolite from Colfax Co., New Mexico (Table 1, No. 2). The trace element distribution in the Wolf Rock has also been kindly determined for me by Dr. S. R. Nockolds (Table 1). Some additional mineralogical data which re-examination of the rock has provided may now be set down.

In addition to nosean and sanidine, nepheline (ω 1·540, ϵ 1·536) is also conspicuous as a phenocryst mineral. It appears in the form of stout hexagonal prisms, often showing growth zones like the nepheline of the Brüx phonolite. Conspicuous is a narrow peripheral zone to the crystals of lower refraction and birefringence probably indicative of a more siliceous composition of this zone of the nepheline solid solution. This outer zone may have associated with it some late stage analcime. Analytical figures for a bulk nepheline separation gave Na_2O 16·77, K_2O 4·35, CaO 1·03 corresponding to $Ne_{79.7}$ $Ks_{15.1}$ $An_{5.2}$ (wt. per cent) or K/K + Na + Ca = 14 atom per cent. An X-ray spectrometer run kindly carried out by Dr. J. D. C. McConnell gave K/K + Na + Ca = 12–13 atom per cent. In the alkali feldspar environment this nepheline is doubtless a siliceous member of the series. The analysis of the contained sanidine executed by Mr. Scoon is given in Table 1 (No. 1a) and shows its composition as $Or_{59.4}Ab_{39.4}An_{0.6}Ce_{0.6}$. The alkali feldspar-nepheline tie line of the rock in the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2 accords with the trend characteristic of a volcanic association. Aegirine is typically a groundmass constituent but occasionally it appears in larger clusters of prisms and these rarely enclose a core of an intergrowth of fine brown biotite and magnetite suggestive of a xenocrystic origin. A rarer mineral hitherto not

TABLE 1

	1	1a	2	3	4	Norm of 1		Spectrographic data on 1 (ppm.)
SiO_2	54·90	65·55	56·24	55·81	56·43			Ga 15
Al_2O_3	22·31	18·88	21·43	23·02	22·25	Or	37·81	Cr *
Fe_2O_3	1·29	0·44	2·01	2·04	2·66	Ab	23·06	V 40
FeO	0·51		0·55	0·83	0·97	Ne	30·39	Mo *
MnO	0·33	0·01	0·08	0·18	tr	Hl	0·46	Sn *
MgO	0·04	0·01	0·15	0·13	tr	Ac	1·62	Li 25
CaO	0·76	0·10	1·38	2·73	1·41	Di	1·08	Ni *
Na_2O	10·16	4·61	10·53	10·02	11·12	Wo	0·52	Co *
K_2O	6·43	9·88	5·74	5·24	2·77	Il	0·46	Sc *
H_2O+	1·36	0·23*	0·86	nil	2·05	Mt	1·16	Zr 450
H_2O-	0·21	0·07	0·12	nil		Th	0·85	Y 15
TiO_2	0·22	0·02	0·26	0·40		Ct	0·50	La 45
P_2O_5	0·04		0·06	0·12	tr	Z	0·27	Sr 650
CO_2	0·22			nil		Rest	1·73	Ba 220
SO_3	0·49		0·10	0·28			99·91	Rb 550
Cl	0·26		0·12	0·13		$(Ne_{47\cdot9}Ks_{23\cdot4}Qz_{28\cdot8})$		Cs *
ZrO_2	0·18		0·09					Ce —
BaO	0·07	0·22	0·08					Cb —
Ln_2O_3	0·05	* Loss on ignition						Th —
Rest			0·06					
	99·83	100·02	99·86	100·93	99·66			
Less O	− 0·06							
= Cl	99·77							

1. Nosean Phonolite, Wolf Rock, Cornwall.
1a. Sanidine from phonolite (1). ($Or_{58\cdot4}Ab_{32\cdot4}An_{6\cdot5}Ce_{2\cdot8}$).
2. Phonolite, Pleasant Valley, Colfax Co., New Mexico. (Washington, *Prof. Paper* xcix, *U.S. Geol. Surv.*, (1917), p. 309).
3. Phonolite, Brüx, Bohemia (Tröger, *Spezielle Petrographie der Eruptivgesteine*, (1935), p. 198).
4. Nosean Phonolite, Wolf Rock (Teall, *British Petrography*, (1888), p. 368).

recorded in any account of the phonolite forms colourless prisms of refraction 1·66–1·67, optically positive, low extinction ($a'\wedge c$) and low double refraction, optically positive, 2V moderate and with noticeable dispersion. Spectographic data on a concentrate of this mineral show that in comparison with the whole rock, the mineral is relatively enriched in the rare earths La and Y and also Zr. In these properties, the mineral accords most closely with a member of the johnstrupite-mosandrite group (cf. Th. G. Sahama and K. Hytönen, (*Geol. För. Förh., Stockholm*, 1957, 491, pp. 791–796.).

DEPARTMENT OF MINERALOGY AND PETROLOGY,
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The Ammonite Zones of the Middle Jurassic Beds of East Greenland

By J. H. Callomon

(PLATES XVII–XVIII)

Abstract

New discoveries have established the presence of nine ammonite zones in the Middle Jurassic beds of East Greenland. The top two are Lower Callovian; the remaining seven yield ammonites unknown from extra-Boreal provinces and are presumed to range down through the Bathonian, possibly into the Bajocian.

I. Introduction

SEDIMENTS of Jurassic age are now well known to occur extensively along the coast of East Greenland between 70° and 77° N. Their geology, and history of research, has recently been summarized in an excellent review by Donovan (1957). In the lower part, thick and probably largely complete Lias follows conformably on Rhaetic and Trias; its facies is partly estuarine, although sharply terminated by marine Toarcian dated by ammonites to lower *Jurense* Zone. The fossil faunas differ little from those of Europe and stratigraphic correlation presents no special problems. The upper Jurassic part of the succession starts in the *Plicatilis* Zone of the Oxfordian, again with faunas of typically N.W. European aspect, and continues with probably few breaks into the Lower Cretaceous.

The Toarcian and Oxfordian are separated by, but are conformable with, up to 600 m. of marine Middle Jurassic. The first few ammonites were brought back by the Danish expedition of 1898–1900 and described by Madsen (1904); but the beds from which they came were not closely examined till 1926–27, when members of the Danish Government Expedition, the first of many to East Greenland led by Dr. Lauge Koch, with few breaks, in the thirty years since, wintered in the Scoresby Sound region. In particular, a large collection of well-preserved ammonites was made by A. Rosenkrantz and submitted for examination to L. F. Spath in London, who published the results in a monograph (Spath, 1932).

With the stratigraphical information at his disposal, Spath deduced the presence in Jameson Land of four successive ammonite faunas, with indications of possibly others. In attempting to correlate these with standard European successions, immediate difficulties were encountered, for the Greenland and European faunas had no species and barely a few genera in common. The closest resemblance appeared to lie between the *Kepplerites* and *Cadoceras* of the top Greenland fauna (*tychonis* horizon) and the fauna of the Kellaways Beds (top

Lower Callovian, *Calloviense* Zone). This left the three preceding Greenland faunas hanging, uncorrelated, between top Lower Callovian and Toarcian. Various estimates of the time-span involved were made. Spath considered the Greenland faunas as ranging down through the Upper Bathonian (although he defined his Bathonian to include zones which are correctly already Callovian), partly to be able to ascribe to each Greenland fauna a time-span which seemed, by general experience, not too short; and partly to allow him to evolve the peculiar Greenland ammonites from well-known European ancestors, the Macrocephalitidae, which he thought themselves appeared not much before the beginning of the Upper Bathonian. Arkell (1956, chapters 22, 28) based his judgment on a view of the Bathonian in the world as a whole; he noted that quite generally the Bathonian was a time of marine regression, followed by an equally general Callovian transgression especially widespread, e.g. over the Baltic and Russian shields. He assumed, therefore, that Bathonian is absent in the Arctic, and placed all four Greenland faunas in the Lower Callovian. A third viewpoint has been put forward by Imlay (e.g. 1952), based not upon the Greenland faunas themselves, but upon very similar sequences discovered in recent years in North America. Here the time-gap is narrowed from below by the presence of normal faunas up to Middle Bajocian. Moreover, there is no evidence of subsequent regressions or discontinuities, and Imlay is led to spread the equivalent of the Greenland faunas over the whole of the Bathonian into Upper Bajocian.

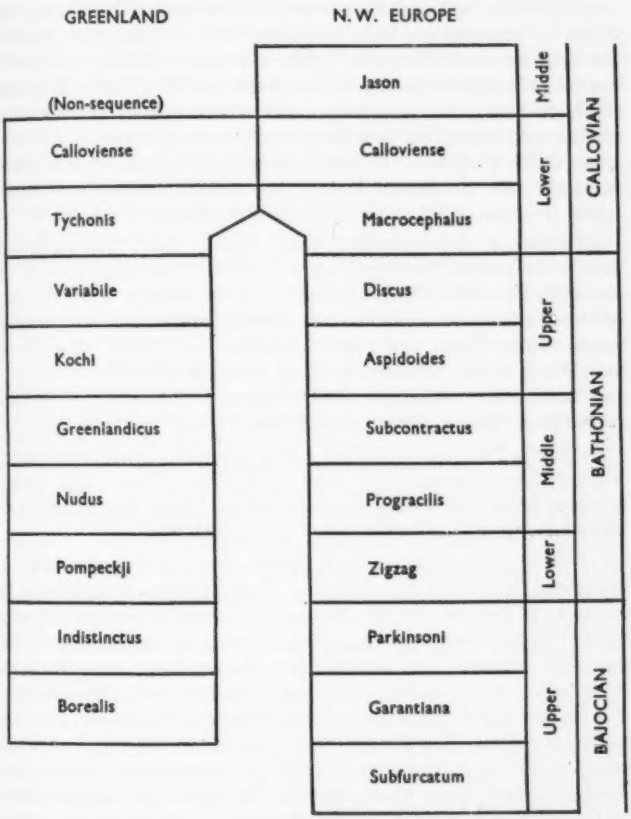
It has been my privilege, as a member of Dr. Koch's expeditions to East Greenland in the summers 1957–58, to re-examine the Jurassic outcrops of Jameson Land. It was possible to record and collect in detail from numerous well-exposed sections and, with the modern techniques of transport which have been evolved, to bring back a considerable collection of ammonites. These have yielded much new information. As publication of full details in *Meddelelser om Grønland* will take time, and as other regions of the Arctic are currently being actively explored, the preliminary results are summarized here.

II. Stratigraphical Results

The Middle Jurassic beds of southern Jameson Land constitute the Vardekløft Formation, replaced in part northwards through facies-changes variously by the Fossil Mountain Formation and Yellow Series. Nine successive and distinct ammonite-zones have now been established. They cover the whole formation but for a ubiquitous lowest series of black shales about 50 m. thick resting on Toarcian, and yielding only plants and rare belemnites. The zonal succession is summarized in Table 1 and notes on the separate zones are listed below.

(*a*) Zone of *Cranocephalites borealis* (Spath). Spath named this species on the basis of a single, wholly septate nucleus in the Rosenkrantz collection (1932, pl. 14, fig. 4) and placed it in *Xenocephalites*,

TABLE 1.



a genus known at the time only from the Andes. A second small but poorly preserved specimen had been collected during the 1898–1900 expedition. It transpires that the species represents one of the commonest and most widespread Greenland faunas. The complete adults are typical *Cranocephalites* and have nothing to do with *Xenocephalites* (see pl. XVII, figs. 1, 2; pl. XVIII, fig. 3).

(*b*) Zone of *Cranocephalites indistinctus* nov. The *borealis* fauna is followed by small, compressed, evolute, feebly-ribbed species hitherto undescribed (see p. 510 and plates). Two specimens figured by Frebold (1958, pl. 8, figs. 2, 3) from Prince Patrick Island are closely similar, and may indicate the zone in Arctic Canada.

(*c*) Zone of *Cranocephalites pompeckji* (Madsen). This is the zone of the " *Cranocephalites* Beds " with the lowest of Spath's four faunas. His tentative subdivision into " *pompeckji* and *subbullatus* horizons " has not been confirmed. Formal designation as Zone was by Donovan (1953, p. 130). The *pompeckji—vulgaris* fauna is by far the most profuse, and prompted Rosenkrantz to write as footnote to a photograph (1929, p. 146): " In the foreground thousands of ammonites lie spread over the ground." It is also known from Prince Patrick Island (Frebold, 1958) and Novaya Zemlya (Sokolov, 1913, pl. I).

(*d*) Zone of *Arctocephalites nudus* Spath: his " *Arctocephalites* Beds ", designated Zone by Donovan (1953). The index-species, as exemplified by the holotype, is atypical of the fauna as a whole; the commonest forms are medium-sized compressed species like *A. ornatus* Spath, *elegans* Spath, and *arcticus* (Newton and Teall). The fauna from Windy Gully, Northbrook Island, Franz Josef Land (see Newton and Teall, 1897; Whitfield, 1906) belongs to this zone; it is also known from Novaya Zemlya (Salfield and Frebold, 1921, pl. 1, fig. 1).

(*e*) Zone of *Arctocephalites greenlandicus* Spath. Large compressed *Arctocephalites*, considerably larger than those of the *Nudus* Zone retaining dense, fine ribbing to correspondingly larger diameters; also inflated forms such as " *Cadoceras* " *crassum* Madsen.

(*f*) Zone of *Arcticoceras kochi* Spath; his " *Arcticoceras* Beds ", designated Zone by Donovan (1953). Now that abundant material is available, it appears that the differences between *Arcticoceras* (dating from 1924) and *Arctocephalites* (1928) lie solely in the character of the secondary ribbing. This becomes very strong, sharp, and coarse in *Arcticoceras*, with a tendency to swing forward on a sharpened venter; it is the first step towards the ultimate extreme of *Chamoussetia* in the *Calloviense* Zone. The average size is large (up to 200 mm. in adults), retaining ribbing to diameters at which the predecessors of the *Nudus* Zone are complete and wholly smooth. The zonal index as exemplified by the holotype is again somewhat atypical and quite rare. *A. ishmae* (Keyserling) from the Petchora belongs in this zone, which is thus present in N. Russia.

(*g*) Zone of *Cadoceras variabile* Spath. In this zone the first true *Cadoceras* is found, taking as criterion a sharp edge between steep umbilical walls and whorl sides. The commonest species are very evolute compressed forms hitherto undescribed; some are evolute

and inflated, e.g. *C. calyx* Spath. All the species are of medium size. Typical *Arcticoceras* also still occurs, some species now with quite acute venter, others with very strong, coarse ribbing to the end. To the latter belong the peculiar forms one of which was figured by Madsen (1904, pl. 10, fig. 2) as ?*Olcostephanus* (a Lower Cretaceous genus), and in a sense Rosenkrantz was correct (1929, p. 147) in referring them "to the cardioceratids". The zone also sees the first appearance in Greenland of *Kepplerites*, mostly small finely-ribbed forms close to the type of *K. tychonis* Ravn and large, compressed finely-ribbed forms resembling *K. antiquus* Spath. The beds are most clearly exposed in northern Jameson Land, near Mt. Mikael and Fossil Mountain, where the overlying zone is poorly fossiliferous; and Spath (1932, p. 31) already noted the difference in general appearance between the "*tychonis*" fauna of Mikael (*Variabile* Zone) and Vardekløft (mostly *Tychonis* Zone) further south. The *Variabile* Zone does occur in the Vardekløft area—indicated in the Rosenkrantz collection by *C. variabile*, *C. franciscus*, *C. calyx*, and *K. tychonis* var. *fasciculata*—but because of steep slopes and screes is there not easily identified stratigraphically. It seems to occur in Spitsbergen, represented by *K. svalbardensis* Sokolov and Bodylevsky.

(*h*) Zone of *Kepplerites tychonis* Ravn; Spath's "*Kepplerites-Cadoceras* Beds", designated Zone by Donovan (1953). The fauna consists of *Kepplerites*, very large *Cadoceras* (*victor* Spath), but no *Arcticoceras*. The exact position of *tychonis* itself is not yet known, for the type came from Store Koldewey island, far to the north, and there are no specimens that exactly match it among those figured by Spath or collected in the last two summers. However, the forms of *Kepplerites* are so variable that at present they have little stratigraphical value, and it seems best to follow Spath in adopting a broad interpretation of *tychonis* for the time being. *Kosmoceras pauper* is not uncommon in this zone, and there is no separate "*pauper* horizon" (Spath); it is merely the microconch of *Kepplerites*.

(*i*) Zone of *Sigaloceras calloviense* (Sowerby). The index is known only from southern England and northern France (see Callomon, 1955) for apparently ecological reasons, but the associated fauna is so characteristic that the same zonal name is used almost universally. This associated fauna has now been found in the top beds of the Fossil Mountain Formation, on Fossil Mountain itself, which are lateral equivalents of shales at the top of the Vardekløft Formation unfossiliferous except for huge petrified treetrunks. The forms found include *Kepplerites* (*Gowericeras*) spp., cf. *crucifer* (Buckman), or *curtilobus* (Buckman); *Kosmoceras* spp. aff. *gulielmi* (Sowerby), one specifically identical with an undescribed species not uncommon in the English Kellaways Rock; *Cadoceras* of the *sublaeve* group;

Pseudocadoceras spp. conspecific with English forms; and *Proplanulites* sp. nov. aff. *koenigi* (Sowerby). The overall resemblance to the fauna of the English Kellaways Rock is most striking. In addition, among ammonites collected by Stauber during the Danish Two-Year Expedition, 1936–38 (Koch, 1955), in the same general area (but from unspecified beds) are nuclei of typical *Chamoussetia*.

Beds of the *Calloviense* Zone are overlain conformably, with a sharp but often inconspicuous lithological change, by black shales or sandstones of the Koch Fjaeld Formation which, in the Vardekløft area, have now yielded *Amoeboceras* and Perisphinctids indicating Upper Oxfordian (*Bimammatum* Zone).

III. Palaeontological Note

Cranocephalites indistinctus sp. nov. Pl. XVII, figs. 3, 4; Pl. XVIII, figs. 1, 2. *Holotype*; pl. XVIII, fig. 1 (no. 1435).

Description of holotype : the specimen is a complete adult, somewhat crushed; maximum diameter 62 mm., septate to about 40 mm., with 5/8th whorl body chamber. The last few sutures are degenerate and approximated; the umbilical seam uncoils; and the peristome is modified by a broad shallow constriction, typical of the genus. The coiling is consistently involute—umbilical width 10 per cent of diameter at 40 mm.—and the whorl-section compressed. The ribbing persists to the end, and is fine but rather feeble and indistinct throughout.

Variability and comparisons : some 30 specimens are available, varying between extremes which, with fewer and better-preserved specimens, would conventionally be classed as several species. The holotype is of average size, but some of the shells become as large as the one shown in Pl. XVII, fig. 3. Others (e.g. Pl. XVIII, fig. 2) are more evolute than the type.

The species resembles the succeeding group of *C. pompeckji* in the style of ribbing, but differs from it in being consistently more feebly and densely ribbed, smaller, and markedly more compressed; the two faunas barely overlap in their range of forms. The new name is here introduced to avoid a *nomen nudum* as zonal index.

IV. Correlation

Correlation of the *Tychonis* Zone with the European *Calloviense* Zone has always been in some doubt, for Spath himself pointed out that Greenland *Kepplerites* (alias *Seymourites*) from this zone resembles European *Kepplerites* sensu stricto (*Am. keppleri* Oppel, *Am. macrocephalus evolutus* Quenstedt, and " *Cerericeras* " *cereale* Buckman) more than *Gowericeras* etc. from the *Calloviense* Zone. Unfortunately

the German *Kepplerites*, although abundant, came from the " Macrocephalenoolith ", a condensed diachronic bed whose age was uncertain in terms of the standard zones, belonging locally to as high as the topmost subzone of the *Calloviense* Zone (see Callomon, 1955). On the other hand, from England, where the zonal ages of the beds are known, only a single, incomplete specimen (*cereale*) was at the time available. Further evidence has since come to light (to be published), and some eight *Kepplerites* s.s. (and one *Toricelliceras*) are now known from English Upper Cornbrash, five definitely from basal Callovian (*Macrocephalus* Zone and Subzone; *Siddingtonensis* brachiopod Zone). Some are practically indistinguishable from syntypes of Quenstedt's *macrocephalus evolutus* (I am greatly indebted to Dr. H. Hölder of Tübingen for furnishing me with casts of Quenstedt's originals), and one from *Kepplerites* (*Seymourites*) *traillensis* Donovan (1953, Pl. 17, fig. 1) from East Greenland. Thus both the Greenland *Tychonis* Zone and the Württemberg (Ehningen) Macrocephalenoolith are now dated to *Macrocephalus* Zone. Final confirmation in Greenland comes from the presence of *Calloviense* fauna above.

There remain seven ammonite zones in Greenland to be accommodated below basal Callovian. The basic difficulty remains, and estimates have still to be based partly on zoological arguments, e.g. the relative durations of ammonite faunas. However, all seven zones must be considered as definitely pre-Callovian and hence at least in greater part Bathonian. Moreover, previous arguments in which the Cadoceratinae and Kosmoceratidae are derived from Macrocephalitidae must fall, for resemblance between the former and, despite Spath's assertions, the only known pre-Callovian forms of the latter—*Morrisiceras*—rapidly decreases on descending down the zones. For a number of reasons the ancestors of both Kosmoceratidae and Cadoceratinae are in my opinion to be sought independently in earlier Stephanoceratáceae. The most likely candidate in the case of the former appears to be *Cadomites-Polyplectites*, known in Europe throughout the Bathonian but commonest in the Upper Bajocian. The earliest of the Cadoceratinae in the wide sense is *Cranocephalites* of the *borealis* group, and its closest resemblance is to *Chondroceras* of the Middle Bajocian. To my mind the most satisfactory picture is obtained by placing the *Borealis* Zone of Greenland in the Upper Bajocian, the others in the Bathonian. In this picture, the great separation of ammonites into faunal realms occurred in the Middle Bajocian, as shown by Arkell; thereafter, following Imlay, the Arctic province evolved steadily and uninterruptedly and the widespread peculiarities of the Bathonian stage stressed by Arkell reside in the European and Tethyan rather than Boreal realms.

I should like to express my gratitude to Dr. Koch for inviting me to

take part in his expeditions; and to thank Dr. E. I. White, Keeper in Palaeontology, for providing me with facilities in the British Museum (Natural History) for working out the Greenland collections.

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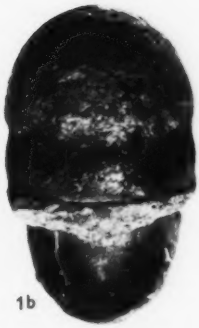
EXPLANATION OF PLATES

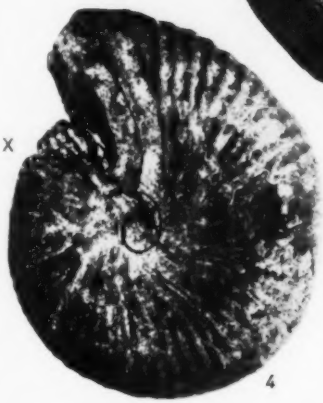
All figures are natural size

PLATE XVII

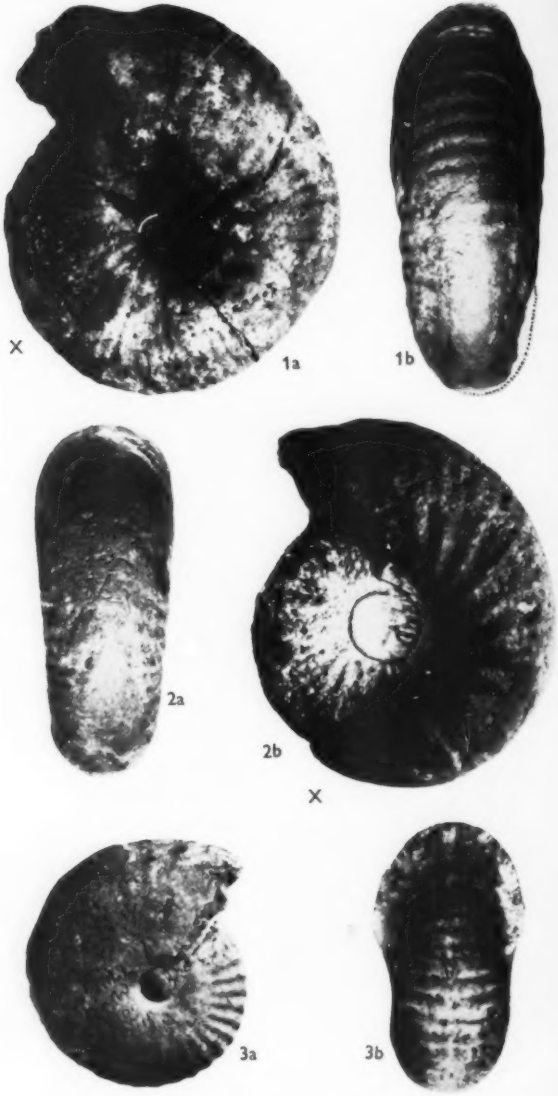
FIGS. 1, 2.—*Cranocephalites borealis* (Spath). Jameson Land: Ugle Elv, north ridge of Teebjaerg. *Borealis* Zone (bed 18).
Fig. 1*a*, *b*: a complete adult, of average size, with peristome (no. 1144).
Fig. 2*a*, *b*: a complete adult phragmacone (no. 1140).

FIGS. 3, 4.—*Cranocephalites indistinctus* sp. nov.
Fig. 3: a complete adult of above average size (no. 1439). Top ridge of Teebjaerg, *Indistinctus* Zone (bed 28).
Fig. 4: complete adult (no. 1306). Ugle Elv, ridge on west side of Statuebjaerg, *Indistinctus* Zone (bed 20).





CRANOCEPHALITES FROM EAST GREENLAND.



CRANOCEPHALITES FROM EAST GREENLAND.

PLATE XVIII

FIGS. 1, 2.—*Cranocephalites indistinctus* sp. nov. Teebjaerg, *Indistinctus* Zone (bed 28).
Fig. 1*a*, *b*: holotype; complete adult with peristome (no. 1435).
Fig. 2*a*, *b*: complete adult; somewhat evolute variety (no. 1437).
FIG. 3.—*Cranocephalites borealis* (Spath). Teebjaerg, *Borealis* Zone (bed 18). Another complete, adult phragmacone (no. 1156).

CORRESPONDENCE

FACIES IN METAMORPHISM AND TECTONICS

SIR,—A difference in usage exists between Turner's recent publication (Fyfe, Turner, and Verhoogen, 1958, ch. 1) and an earlier one (Turner and Verhoogen, 1951). The recent recommendation is more compatible with custom in fields other than that of metamorphism. However, the earlier is a widely known text. It is therefore opportune to clarify the difference and perhaps, in so doing, to emphasize a parellelism between metamorphic, structural, and sedimentary terms.

" Facies " can be used to refer to present-day observable properties—

" This sample is a sandy facies of a horizon which is commonly silty."
" This sample is a folded facies of a bed which is elsewhere found fractured."
" This sample is a diopside-quartz-calcite facies of a rock occurring nearby as limestone."

On the other hand, there is a tendency to use the same term in referring to conditions which existed some time ago " . . . a littoral facies . . . "
" . . . a more deeply buried facies . . . "
" . . . a high-temperature facies . . . "

Consequently, two series of definitions are possible—

(*a*) " The ' sandy facies ' is the facies of rocks whose grain-size range is such and such."

and (*b*) " The ' littoral facies ' is the facies of rocks which were deposited between the low and high tide lines."

Using a series of definitions such as (*a*), the assignment of a rock to a facies is a matter of observation ; using definitions such as (*b*), the assignment is a matter of conjecture. Permissible sentences are then " This rock of sandy facies is thought to be of littoral facies ", etc. The two uses are convenient as long as they are clearly distinguished ; but if " a facies classification " is set up (in the singular) it must be quite clear whether genetic or observational pigeonholes are intended.

Turner's recent classification is unambiguously observational. In spite of the retention of some facies-names, this is something of a change from the earlier work quoted. In the earlier work (p. 446), the Amphibolite Facies as defined embraced that range of temperature and pressure for which the assemblage hornblende-plagioclase is stable. Although minerals were used as criteria, the entity recognized was a range of conditions, and it was a matter for conjecture whether or not the pair, for example, andalusite-muscovite was stable in the same range. In the recent recommendations, the form of definition is a list of assemblages ; andalusite-muscovite is associated with hornblende-plagioclase by arbitration. The conjecture just mentioned should now be rephrased—" to what extent do the assemblages grouped together by definition actually overlap in stability fields ? " To

those whose business is description, the change is beneficial, for the processes of conjecture and of assigning rocks to facies have been divorced. The only loss is that petrologists no longer have a handy phrase to express " that range of physical conditions, whatever it may be, within which the pair hornblende-plagioclase is stable ". The nearest approach may be " the hornblende-plagioclase stability field ". Some such phrase seems necessary to express concisely those conjectures, so crucial, at which petrography and experiment both aim, e.g.—

" the stability field of hornblende-plagioclase encloses entirely that of andalusite-muscovite "

or " . . . overlaps only partially . . . "

A parallel may now be noted thus :

observation	conjecture
sandy facies hornblende-plagioclase facies (1958)	littoral facies hornblende-plagioclase stability field

In the case where the past conditions can be described from present knowledge, " facies " may be used for both observation and conjecture ; but in the case where the past conditions can be referred to only obliquely (" Those conditions, whatever they may be, in which hornblende-plagioclase is stable "), the mineral names occur twice and so " facies " should only be used once ; otherwise conjecture and observation would be indistinguishable.

Turn now to tectonic terms. Harland proposes (1956) that form, scale and composition should be included in a description of a tectonic facies. An example is " isoclinal fold, amplitude 1,000 feet, of a shale unit 100 feet thick ". Abbreviating, we may use this form to express conjectures such as—

" The isoclinal 1,000′ × 100′ shale folds and the nearby 500′ × 500′ × 40′ limestone folds were formed under similar conditions."

(It is not the present concern to discuss fold description ; a concise quantitative scheme is obviously possible. See for example the proposal of Matthews (1958).)

Generalizations will arise such as—

" This association is so common that 500′ × 500′ × 40′ limestone folds are put in the isoclinal 1,000′ × 100′ shale fold facies."

and " It is thought that all the structures so grouped in the isoclinal 1,000′ × 100′ shale fold facies were formed under similar conditions."

The conformity with Turner's recently recommended usage is exact ; but again a need arises for a term for a set of conditions, as yet unknown, which can be referred to by a specific example (" Those conditions, whatever they were, in which such and such a fold was formed "). Perhaps simply " field " will serve, e.g. " stability field " in the metamorphic discussion above.

With the foregoing remarks in mind, the relation of a tectonic facies to a regime may be re-examined (Harland and Bayly, 1958). Harland (1956) used " facies " to refer both to things observable now and to conditions in the past—to both " facies " and " fields " as here used ; but the two terms are retained in the following section as a convenience at least temporarily.

Suppose a field acts upon part of a rock mass, and deformation results. The facies of that part can then be observed and described in terms of form, scale and composition. Since the field conjectured will involve among other things three principal stresses, it can at this stage if desired be put in one of the four classes described by Harland and Bayly (1958, p. 91). If the orientation of the structure is determined, the statement of its facies and its orientation will describe its style ; at the same time, the field can be suggested as belonging to a particular regime.

In a more complex case, the style observed may point to a sequence of events and so to a sequence of fields. Each field will belong to a particular regime, so that a sequence of regimes is also implied. With regard to facies, it is held that only one facies can now be observed ; it may be " isoclinal 1,000′ × 100′ refolded open 200′ × 1,000′ × 100′ on perpendicular axes, schist " and it might be inferred that the facies of the rock at some earlier time was simply " isoclinal 1,000′ × 100′ shale " ; but it is held that in tectonics a rock *is* of only one facies at the present time.

Turner's review of the facies classification makes an opportunity to distinguish observation from conjecture. It has been the purpose of these remarks to seize upon the opportunity and to note how a close correspondence in meaning can be preserved between metamorphic and tectonic terms.

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CULM STRATIGRAPHY

SIR,—Professor Scott Simpson has recently presented (*Geol. Mag.*, xciv, 201–8) a review of Culm stratigraphy which I can in general accept without reservation. An aspect which needs clarification, however, is the stratigraphic succession in the Greywacke Group and the Central Devon Group. Greywackes undoubtedly succeed the Limestone and Chert group both in North-West and in North-East Devon, but with the intervention of a thin shaly and silty series of Namurian age. Greywacke deposition begins, however, at different times; in the north-west later than R_2 (my own observation) in the north-east before R_3 (J. M. Thomas, unpubl.), in the south-west before *H* (Owen, D. E., 1950). Provided that the Greywacke Group is taken to include all beds above the top of the Cherts, which seems a reasonably homochronous line, there seems no objection to the use of the classification here.

I have, however, grave doubts as to the value of the Central Devon Group as a stratigraphic term. It is an indication of our lack of knowledge of these beds that Scott Simpson can describe them as consisting of " facies similar to the Millstone Grit " whilst Ashwin (unpubl. thesis, Univ. of London) refers to the same rocks as exclusively greywackes. In the north-west I can demonstrate that the strata of Coal Measure type in which the early Westphalian flora and fauna are found (i.e. the Morchard type of Ussher) pass upwards into more greywackes, these higher greywackes being Ussher's Eggesford Grits. There is no doubt that these two facies recur in various parts of Central Devon, but whether the repetition is structural or stratigraphical is a problem which only careful mapping can solve. In the north-east the Coal Measure type is apparently absent, and greywacke deposition is continuous. Thus until further evidence is available, I feel it would be unwise to suggest that the succession is simply greywacke followed by non-greywacke deposition.

I find it particularly pleasing that Scott Simpson finds much to approve in

the work of Ussher ; my own work in Devon leads me continually to increased respect for his authority and judgment. To my mind it is particularly unfortunate that his classification, based on a unique knowledge of the Culm, should so long have been ignored.

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28th October, 1959.

SIR,—The publication in your last issue of Mr. Butcher's letter has anticipated a spontaneous retraction of my heresy (which was also that of A. Somervail) and also a letter from Dr. Dearman, along the same lines as Mr. Butcher's which he had courteously discussed with me in correspondence.

There is no doubt that Mr. Butcher is right in concluding that I was mistaken in supposing that the Ugbrooke Group is post-orogenic. I had come to this conclusion myself as Mr. S. C. Matthews has found that in the area south of Callington the members of this Group are undoubtedly inverted in some places. It follows that there is now no conclusive evidence that the Ugbrooke Group is younger than either the Central Devon or Greywacke Groups.

Mr. Butcher's discovery of *Homoceras* near the River Inny is obviously of great interest. I note, though, that he forbears from saying that his fossils are actually out of the Ugbrooke Group rocks. Dr. Selwood allows me to say that he has also found goniatites in this area which are, however, undoubtedly derived, though occurring in the Ugbrooke Group. I think the possibility still remains that the Ugbrooke Group are the youngest sediments of the region.

I do not accept that my error could have been avoided by careful reading of the Survey Memoirs. I am well aware of the passages to which Mr. Butcher refers. The evidence is conflicting and the Survey Officers themselves did not know how to interpret it.

The cleavage problem remains a very interesting one. It is a fact that the Ugbrooke Group rocks do not show the kind of slaty fissility seen in other formations (even when the rocks are highly argillaceous) and this is true of the area south of Callington where they are certainly involved in recumbent structures. The presence or absence of slaty fissility must reflect different styles of tectonic deformation, and the problems presented by the juxtaposition of such differing styles, particularly in South Devon, remains to be investigated.

I do not think the situation at Altarnun is so simple as Mr. Butcher suggests, but I will not comment on this as Dr. Dearman is now working on the area and will no doubt be able to describe the true facts in due course. Moreover I do not question that the Ugbrooke Group enters the Dartmoor aureole as Mr. Butcher has demonstrated.

I welcome Dr. Prentice's communication and need only say that I have no doubt that when his researches are completed he will be able to suggest a better way of dealing with the formations I have lumped together as the Central Devon Group. Until these formations are delimited stratigraphically and on the map the term may be of some use.

S. SIMPSON.

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11th November, 1959.

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